INVESTIGATION OF THE POTENTIAL UTILITY OF MANATEE ALERTING DEVICES

PHASE ONE:

ACOUSTIC WARNING SYSTEM TO ALERT MANATEES OF APPROACHING VESSELS

Final Report
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The Florida Fish and Wildlife Conservation Committee
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and

The Florida Inland Navigation District
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OVERVIEW

This report details the design and development of prototype Manatee Alert Devices (2). The development represents the initial phase of our larger proposed study to investigate the effectiveness of Manatee Alert Devices (MADs) to warn manatees of approaching watercraft. This report specifically presents data on the design specifications, materials, operation, calibration and performance of two Engineering Development Model (EDM) prototypes. The EDM prototypes incorporate all necessary signal generators and electronics into a small light-weight, water-tight package for placement on boats. These EDM prototypes are designed to be rugged, technically robust and accessible to enable a degree operational flexibility in the field. Though initially designed for use with recreational watercraft, MADs have expanded applications for large commercial vessels and barges. The hulls of these large vessels typically radiate very loud propeller noise off the sterns and sides while "blocking" forward projections and casting Acoustical Shadows directly in front of the vessels [1,2,3,4,5]. Manatees in the direct line of approaching barges can not acoustically detect the danger. If positioned off to the side of an approaching vessel, manatees may even seek refuge by moving into the vessel's direct path where it is relatively quiet. The rational for testing MADs is based on sound science with rigorous controlled measurements of the manatees' auditory abilities, (including audiogram, temporal integration, masked thresholds, critical masking ratios, and directional hearing) together with direct physical acoustic measurements in manatee habitats, (ambient noise, motor boat and ship noise characteristics and propagation, and shallow water and near surface acoustic propagation). The data for these investigations has been reported in pervious technical reports to the Florida Marine Research Institute as well as the Army Corps of Engineers and Department of Defense and published in the literature [1-16]. Some of the data and rationale are also summarized for the layman in an American Scientist article *Manatees, Bioacoustics and Boats* attached as Appendix B. These carefully conducted calibrated acoustic measurements of manatee hearing, boats, and habitats were supervised by Dr. Joseph E. Blue, former head of the Navy laboratory that specialized in highly accurate underwater acoustic measurements as the nation's bureau of standards for underwater acoustics (a function relegated to the Navy laboratory by the National Bureau of standards). These investigations, coupled with the knowledge of both linear and parametric sonar, have contributed to the development of the Manatee Alert EDM prototypes. The design specifications presented in this report are rooted in transducer theory pioneered by Dr. Blue and which is further elaborated upon in Appendix A.

This project was funded by the Florida Fish and Wildlife Conservation Commission and The Florida Inland Navigation District.

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I. Introduction:

While manatees are repeatedly scarred and often killed by collisions with watercraft, the root causes of collisions, and how to effectively mitigate the frequency of collisions is greatly debated. Gerstein and Blue have postulated that near surface and shallow-water noise propagation characteristics in concert with the manatee's unique auditory constraints are the underlying sensory causes of most collisions with boats, tugs and barges. While encounters with slow moving commercial vessels are often fatal, most collisions with recreational boats are not, and many individual manatees bear the scars from multiple boat encounters. Gerstein and Blue postulate that the majority of fatal commercial and as well as non-fatal recreational boat collisions result when propagation loses and masking from background noise interfere with the ability of manatees to effectively hear and locate the sounds of vessels. This happens when wild ambient noise is louder than the resulting propeller noise projected forward of approaching vessels. The sounds produced by slower propeller rates are very often effectively masked by natural ambient levels and by the sounds of distant faster moving vessels in manatee habitats.

A comprehensive and rigorous series of psychoacoustic tests using two captive-born manatees mapped the perceptual hearing and the directional hearing sensitivity of manatees under controlled acoustic conditions. The behavioral audiogram and masked threshold experiments provide definite measurements of manatee hearing, localization and integration of auditory information against quiet and noisy ambient conditions. While measuring and defining the limits of manatee hearing Gerstein and Blue quantified the frequency range and specific signal characteristics (pulse rate, duration, frequency modulation and rise characteristics) that manatees can hear and localize best under the most competitive acoustic conditions. These signal parameters are exploited to produce a set of highly directional low intensity signals through

Manatee Alerting Devices. After acceptance of our pending USFWS permit application and receipt of adequate funding, these prototypes will be used to investigate the reactions of manatees to controlled boat approaches with and without the MADs. The scope of this particular work effort has been limited to the staged development and evaluation of two engineering prototypes of the MAD.

II. System Design

The design of the system employs nonlinear (parametric) acoustic methods. Multiple ultrasonic frequencies result in difference frequencies, or parametric waves, that project forward. Imagine two oscillators, one at 200 kHz, the other at 180 kHz. The difference frequency or parametric wave produced underwater would be at 20 kHz. The use of this parametric technique enables the use of a very small projector to produce a very narrow directional beam with negligible side lobes. Also, the beam would be nearly constant over a wide range of frequencies. Linear techniques would require a very large projector to obtain the same directional aspect. This size (~3-ft wide x 1.5-ft high) would not be practical for attachment to most recreational boats. The use of a modulated high frequency signal waveform and the consequent high directivity is a concept that is well known in parametric arrays and was pioneered and applied in underwater projectors by Drs. Thomas Muir and Joseph Blue(17, 18). More recently, the principle has also been used in highly directional audio systems. In both cases, the medium non-linearity is used to demodulate the mixed high frequency carrier and the desired lower frequency waveform. The demodulation process is not linear, and it turns out that Single Side Band Modulation (SSB) appears to be one of the best methods of modulation for reconstruction of the desired lower frequency waveform. The simple theory for the generation of difference frequency sound from the nonlinear interaction of two higher frequency primary waves in water was first developed by Dr. Joseph E. Blue in 1971 and appears as Appendix A.

III. Prototype Hardware

The prototype system consists of a single side band generator (SSB) and combiner, power amplifier parametric acoustic projector and an off-the-shelf MP3 player for imputing 10-20 kHz band signals.

III A. The Modulation System

Modulated 10-20 kHz signals were derived from psychoacoustic investigations with manatees and stored as MP3 files are imputed directly into the SSB and combiner electronics. The signals then pass through a lower sideband (LSB) generator using the phase shift method of single sideband generation with respect to an internally supplied carrier frequency of 200 kHz. The LSB signal from 180 to 190 kHz is linearly summed with the sinusoidal 200 kHz carrier signal, with the carrier level exceeding the LSB level by 10 dB. The modulation scheme chosen is a single sideband full carrier with the upper sideband being suppressed by using the phase shift method. A block diagram representation of the SSB and combiner system is shown in Figure 1. Note that the gains of the individual stages can be varied by the user. This allows the relative level of the carrier, sideband and gains to be individually monitored and set for subsequent field tests with wild manatees.

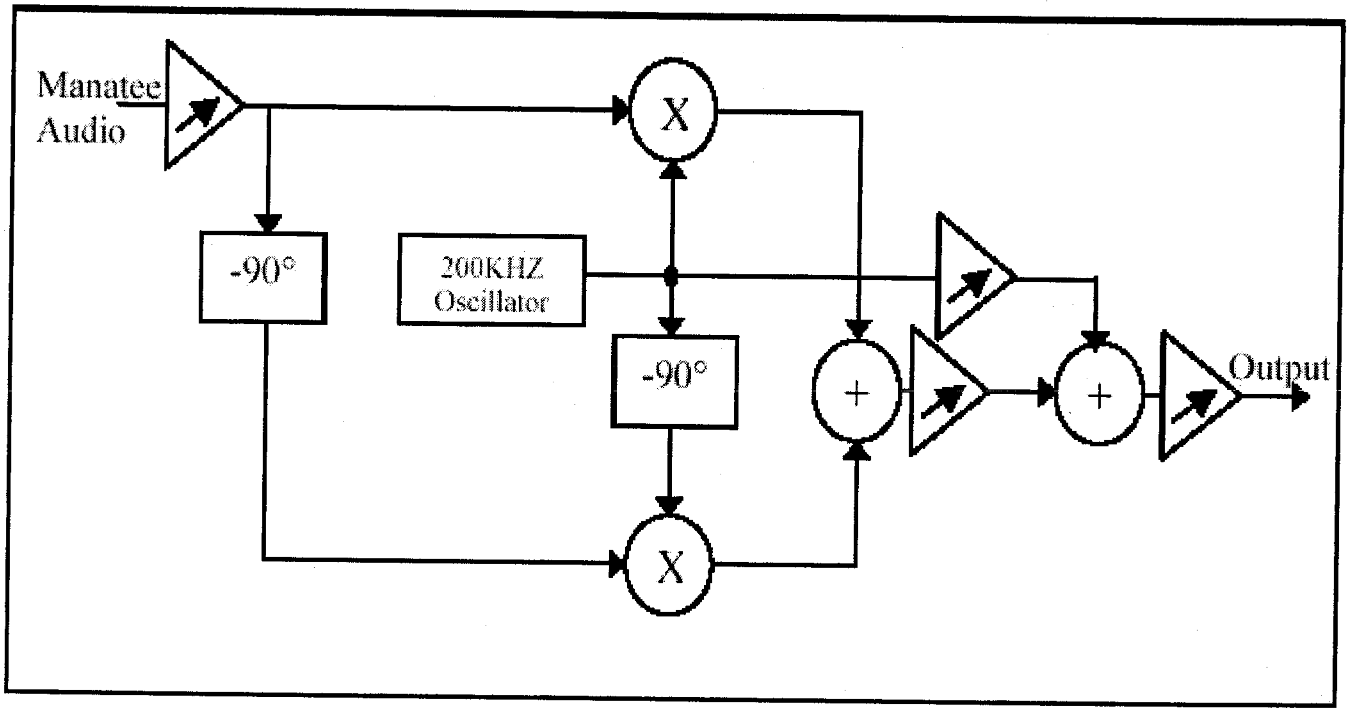

Figure 1. Single Side Band Generator using the phase shift method and combiner.

III B. System Layout :

A general schematic of the signal generation system is provided below in Figure 2. The MP3 signal input and output transducer connectors are on the exterior of the case The modulation board (SSB and summer / mixer) is housed in a shielded enclosure. The power amplifier is mounted onto a heat sink and a 12 V DC power input supplies two DC-DC converters. The power supplies are switched by an ON/OFF lamp-switch. A fuse and reverse polarity protection diode is configured for fault conditions.

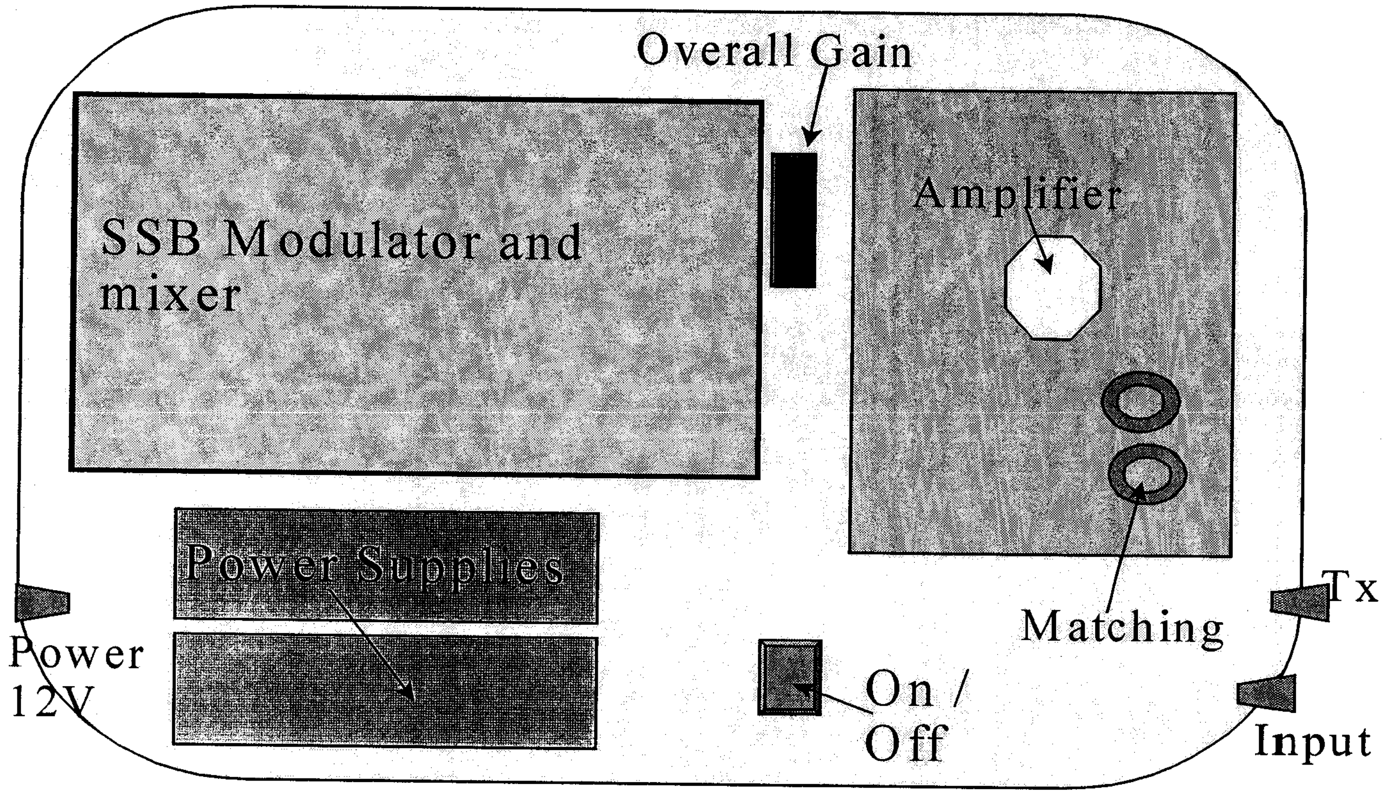

Figure 2 : Schematic of the system layout.

III C. Power Amplifier:

The resulting two-frequency composite signal output of the SSB and combiner is amplified using a linear power amplifier. The device chosen was the APEX PA09 driven from a ± 24 V DC supply. The PA09 is a linear operational amplifier capable of sourcing 2 Amps (rms) to 1 MHz. The gain of the power amplifier is fixed, thus the overall gain of the system is set by using a potentiometer on the outside of the SSB enclosure. The input to the amplifier will not exceed 3 Vp-p as the PA09 is designed to accept a maximum of 11 Vrms. This device is a linear device so a certain amount of heat is generated and dissipated on the heat sink provided. The systems connect to external 12-volt power supplies (via boat batteries) and are housed in watertight pelican cases and are pictured in Figure 3.

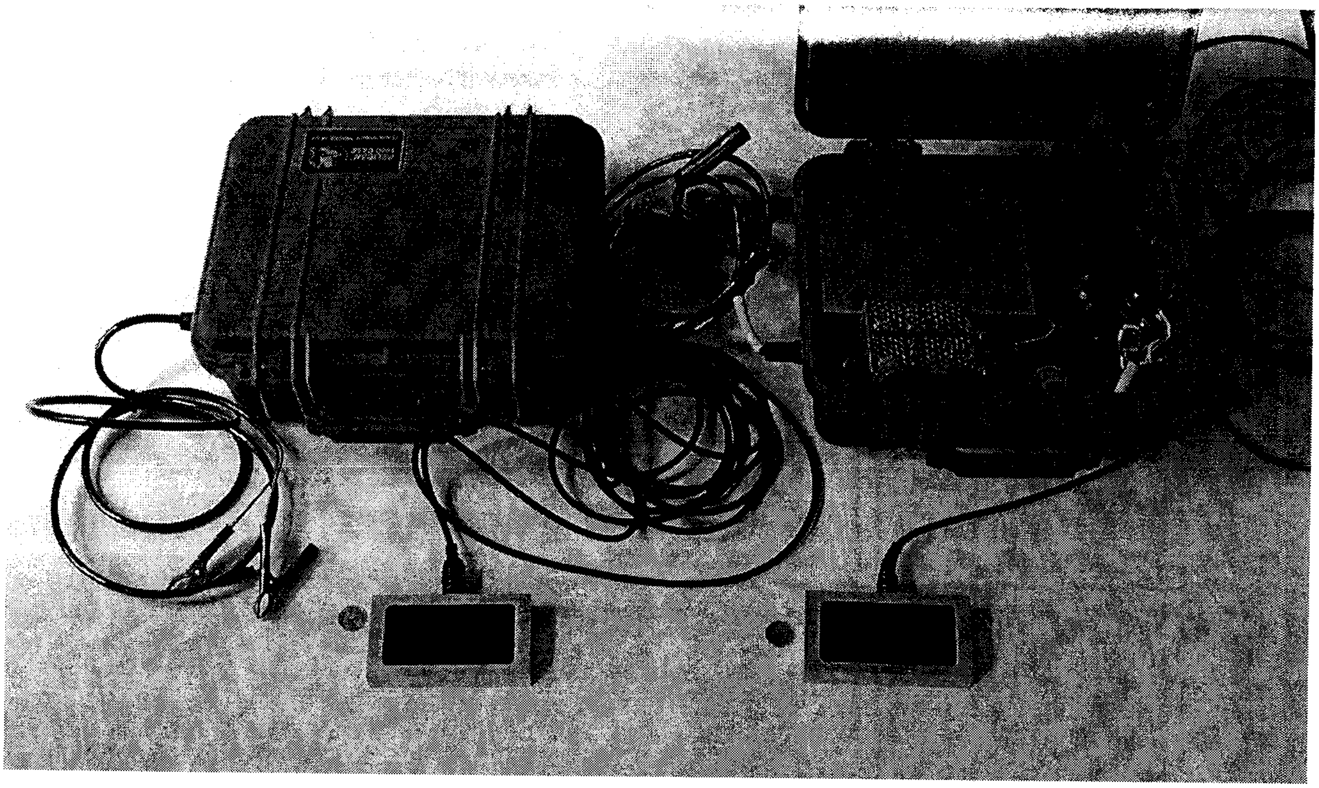

Figure 3 Single Side Band Generator (SSB) and Combiner, Power Amplifier and Acoustic Projector.

III D. Matching Network and Acoustic Projector:

A step-up transformer and fixed reactive component (in parallel) are used in matching network to drive a projector. Each projector is a 45 element planar array, (5 rows of piezoelectric piston elements with 9 elements per row), band centered to transmit the 200 kHz carrier frequency and the LSB signal (Figure 4). The projector has a static capacitance of 2.3 nF. A 0.7-ohm resistor in series with the transformer primary is included to insure amplifier stability and reduce offset errors. The elements are housed in an aluminum housing with coperene between the back of the elements and the housing to give the 40 dB front to back radiation ratios shown on the directivity plots in Figure 13 and 14. Navy Type I ceramic was chosen for its good piezoelectric and thermal properties. Its high Curie point (~ 325 degrees C) insures the projectors can withstand the high temperatures that could be built up if we chose to operate in a continuous wave mode.

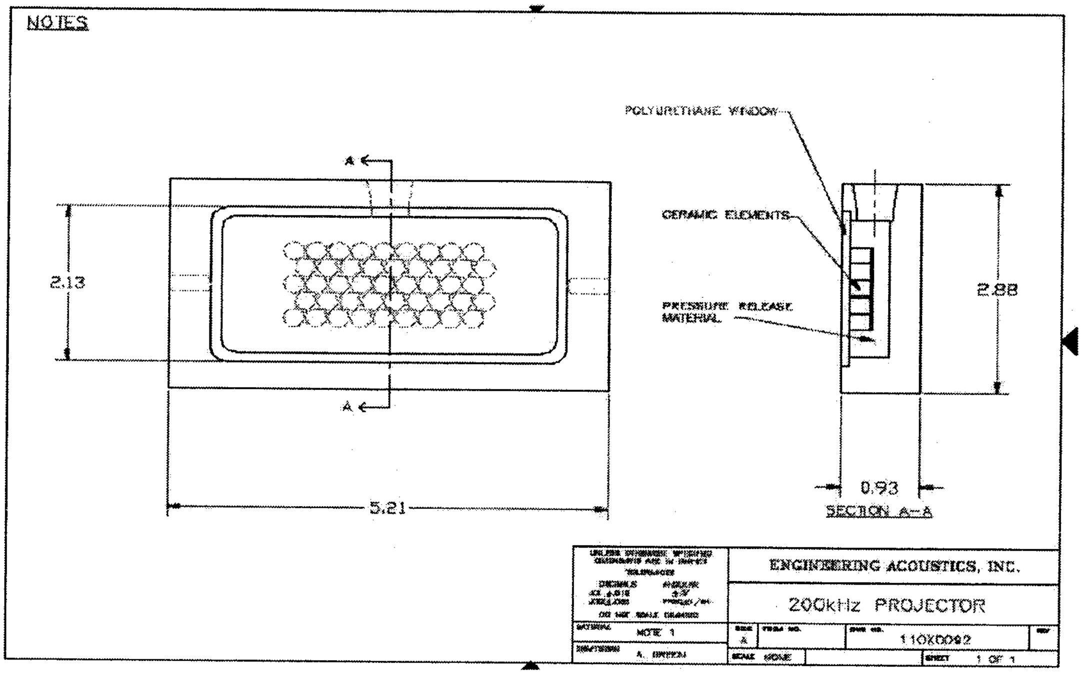

Figure 4. Layout of the thickness mode resonance projector.

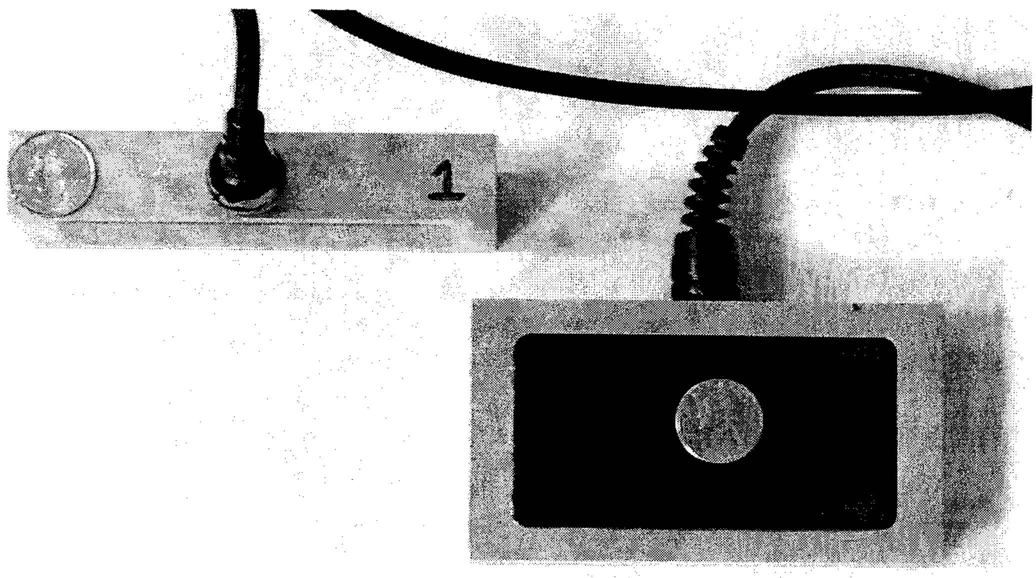

Figure 5. Finished prototype projectors

The projectors pictured in Figure 5 are encased in Aluminum 6030 and structurally reinforced for universal mounting. The dark face is a polyurethane acoustically transparent window that protects the active elements within the housing. These projectors can be through-the-hull or transom mounted. Their small size insures negligible drag on the smallest of boats.

III E. The Single Side Band (SSB) Modulator :

The transducer EDM's prototypes are designed with some flexibility to modify and fine tune in the field during tests with wild manatees. The system board has been left assessable to be able to monitor outputs on deck for quality assurance monitoring during tests with manatees. The oscillator's frequency is tuned to the center frequency of the array. The carrier 90° phase shift can be monitored at pin1 on IC5 and pin 6 on IC6. The signal on Pin6 IC6 should always lag the signal on pin1 IC5 by 90°, and if needed , can be fine tuned by using potentiometer P3. The input amplitude is set to approximately 2V Pk-Pk and can be adjusting using P1. The amplitude of the lower sideband can be adjusted by using potentiometer P4 and the amplitude of the 200 kHz carrier can also be adjusted by using potentiometer P6. The overall output amplitude can be adjusted by varying potentiometer P5 on the side of the SSB modulator enclosure (Figure 6).

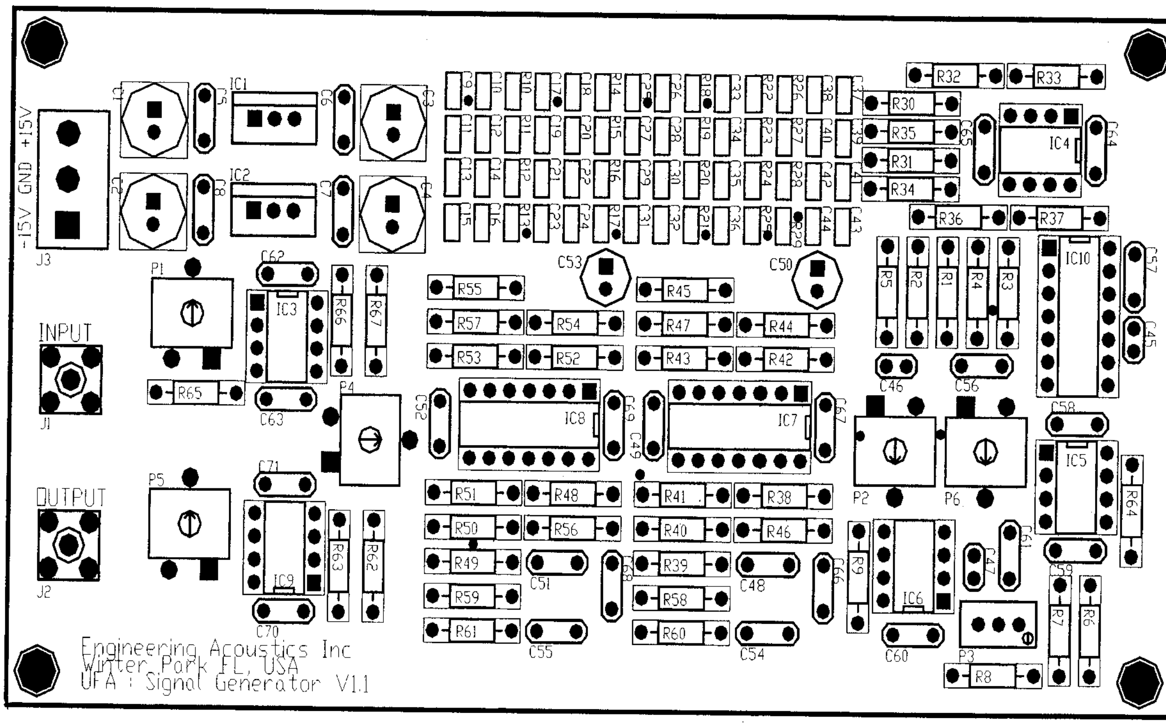

Figure 6. SSB component layout. P5 is an external potentiometer

IV. Bench Calibrations:

Impedance and signal output were measured and captured by using an Agilent Spectrum Analyzer. A function generator was used to simulate the range of 10-20 kHz input signals. The Spectrum Analyzer was configured to hold the maximum readings, this allows for the full band of input frequencies to be represented in one screen capture. Figures 7 and 8 show the results when the carrier and sideband amplitudes are compared.

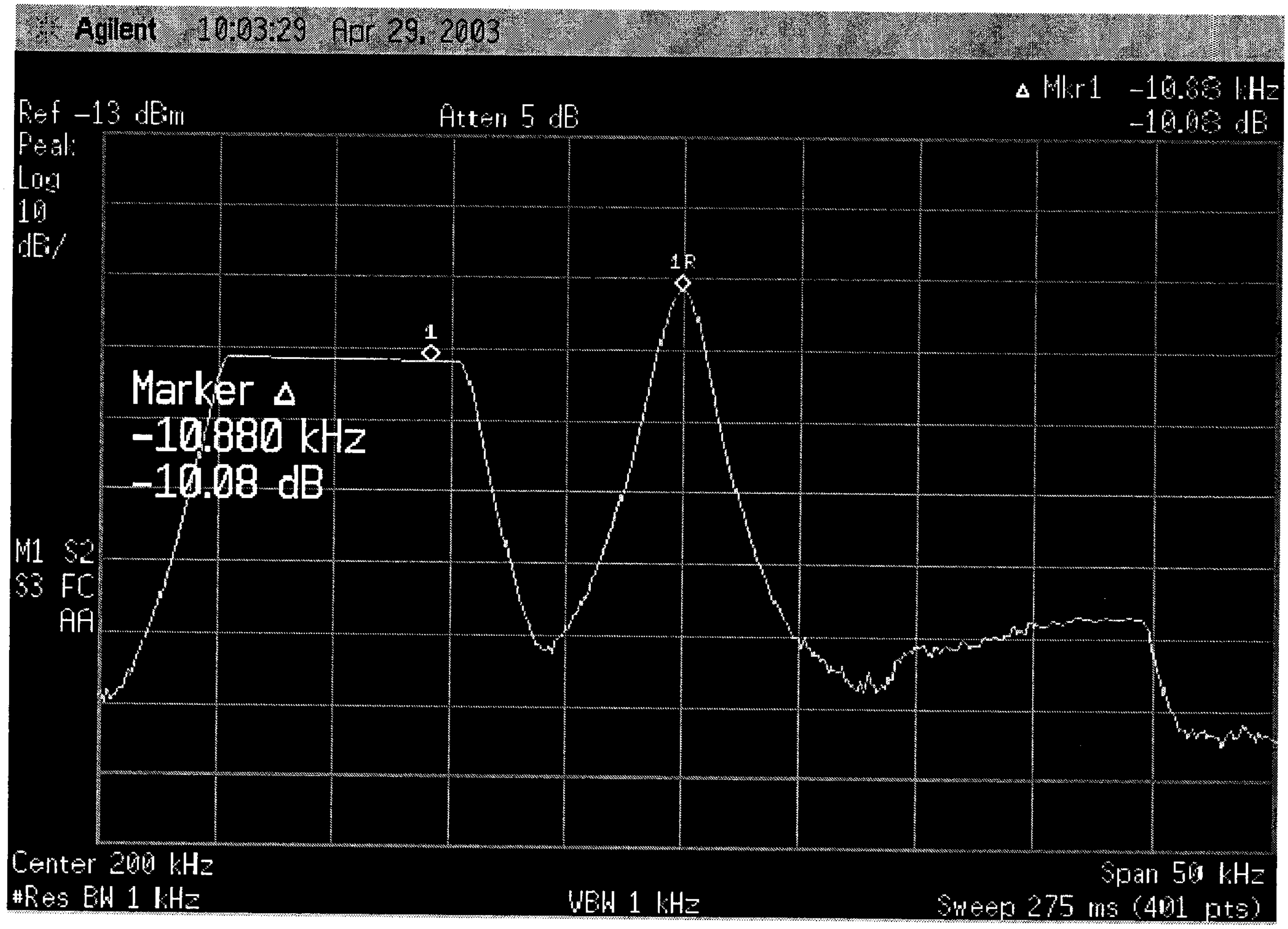

Figure 7. 200 kHz carrier wave compared with the lower side band

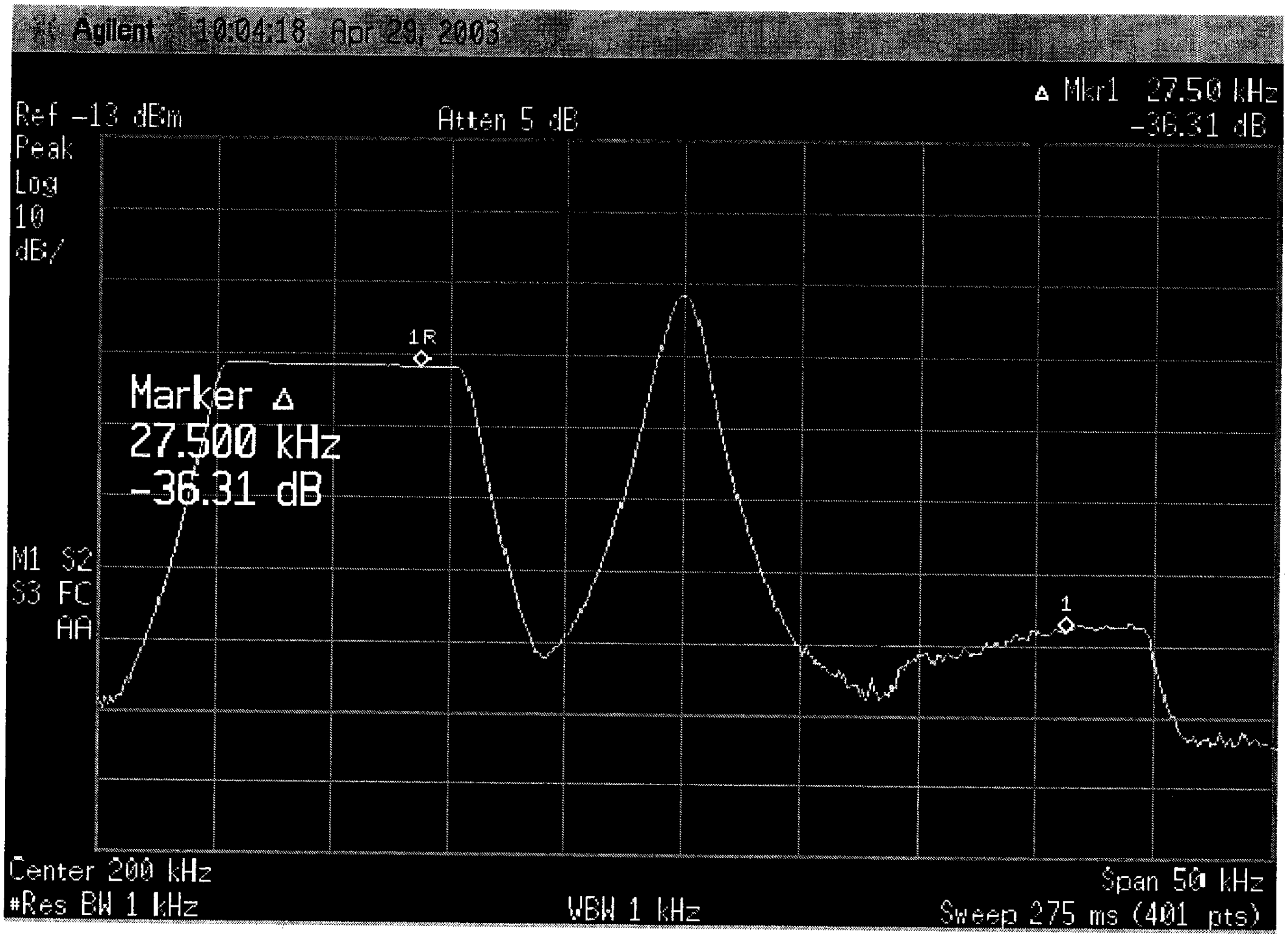

Figure 8: Upper side-band attenuation with reference to the lower sideband with 200 kHz carrier wave

The transfer function model presented in Figures 9a, b, and c and the direct measurements Figures 7 and 8 indicate that the levels of the side-band are predictably 7 dB's down from the carrier. For the levels in the water to have the lower side band 10dB below the 200kHz carrier, the input voltage levels on the system need to be approximately 0.707 times that carrier voltage level. Note that to avoid amplifier saturation, the combined and individual waveforms measured at the summing stage will still be less than 3 Vp-p at full output gain. The SSB modulator has been kept accessible to monitor and adjust levels.

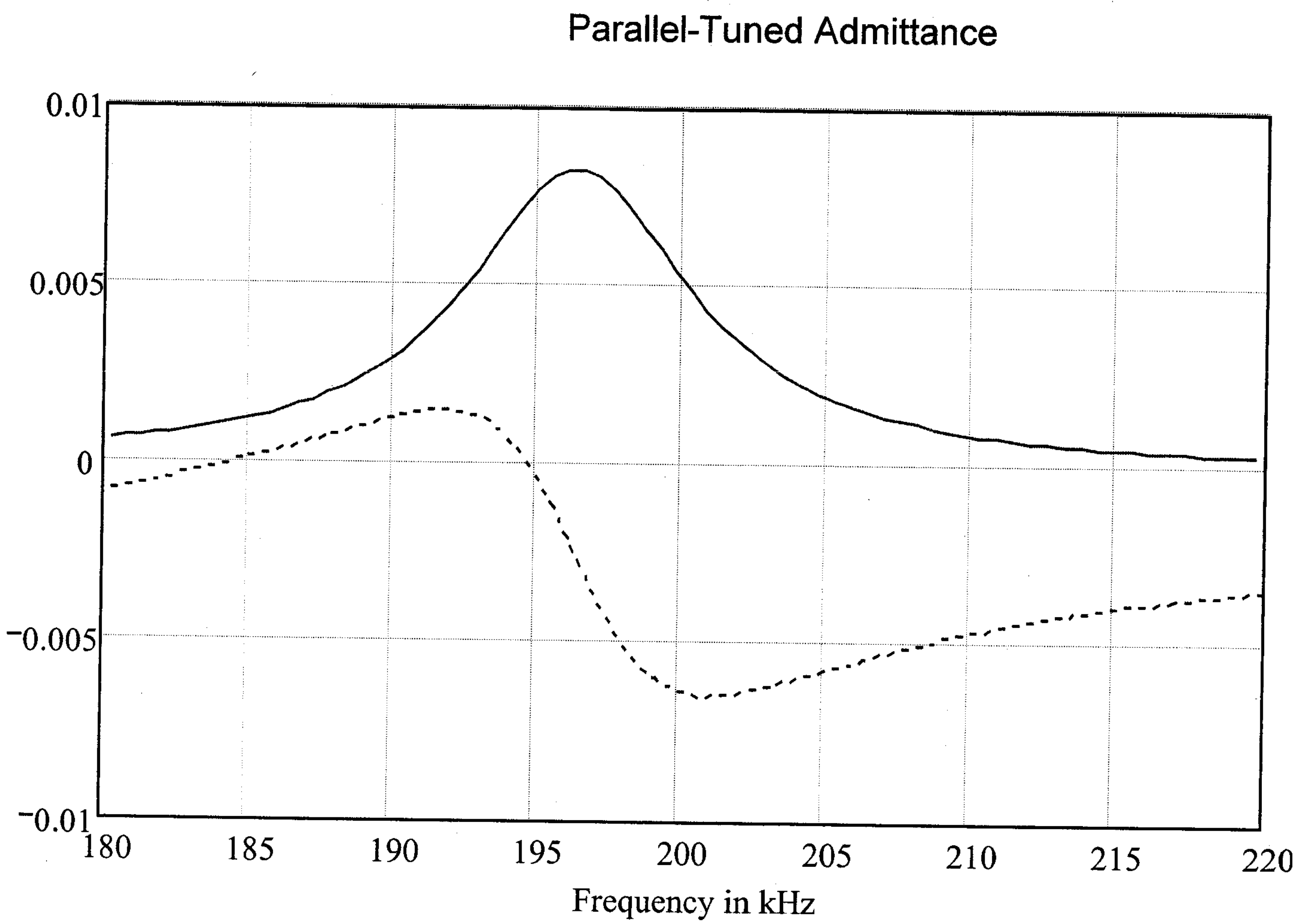

Figure 9a. Mathcad model

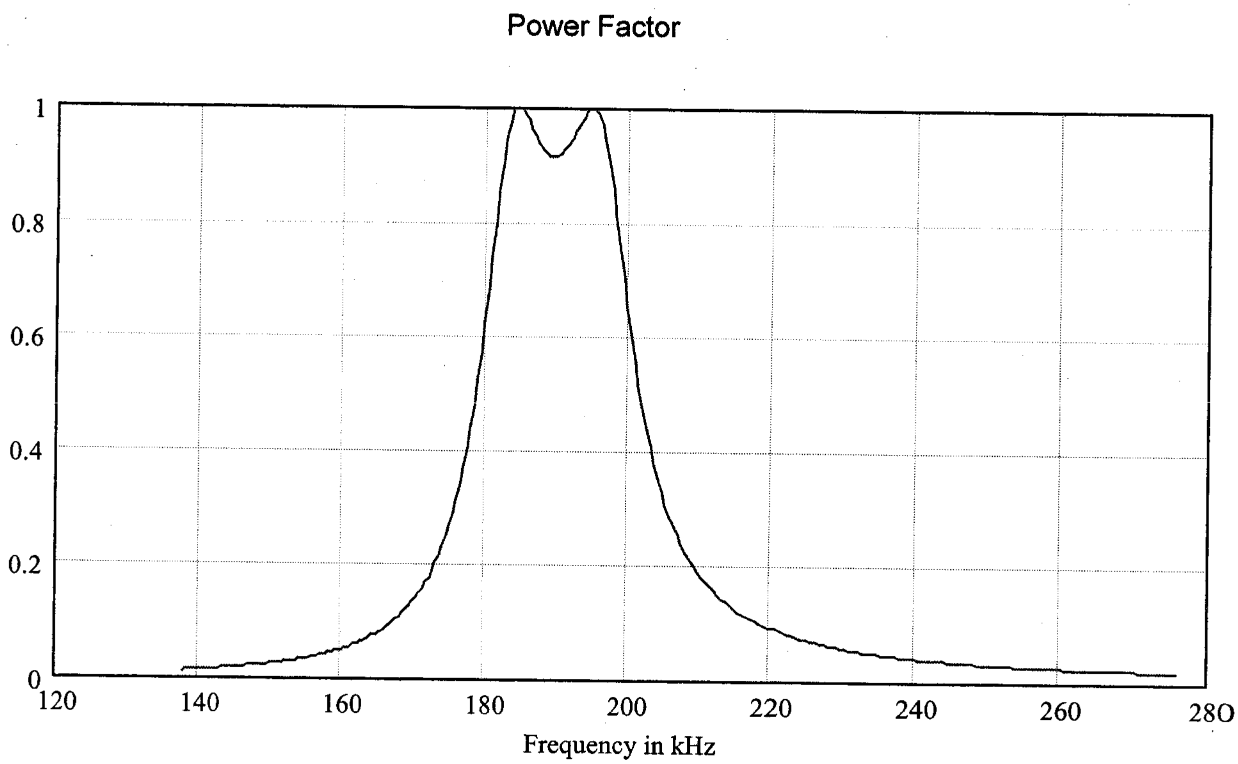

Figure 9b. Mathcad model

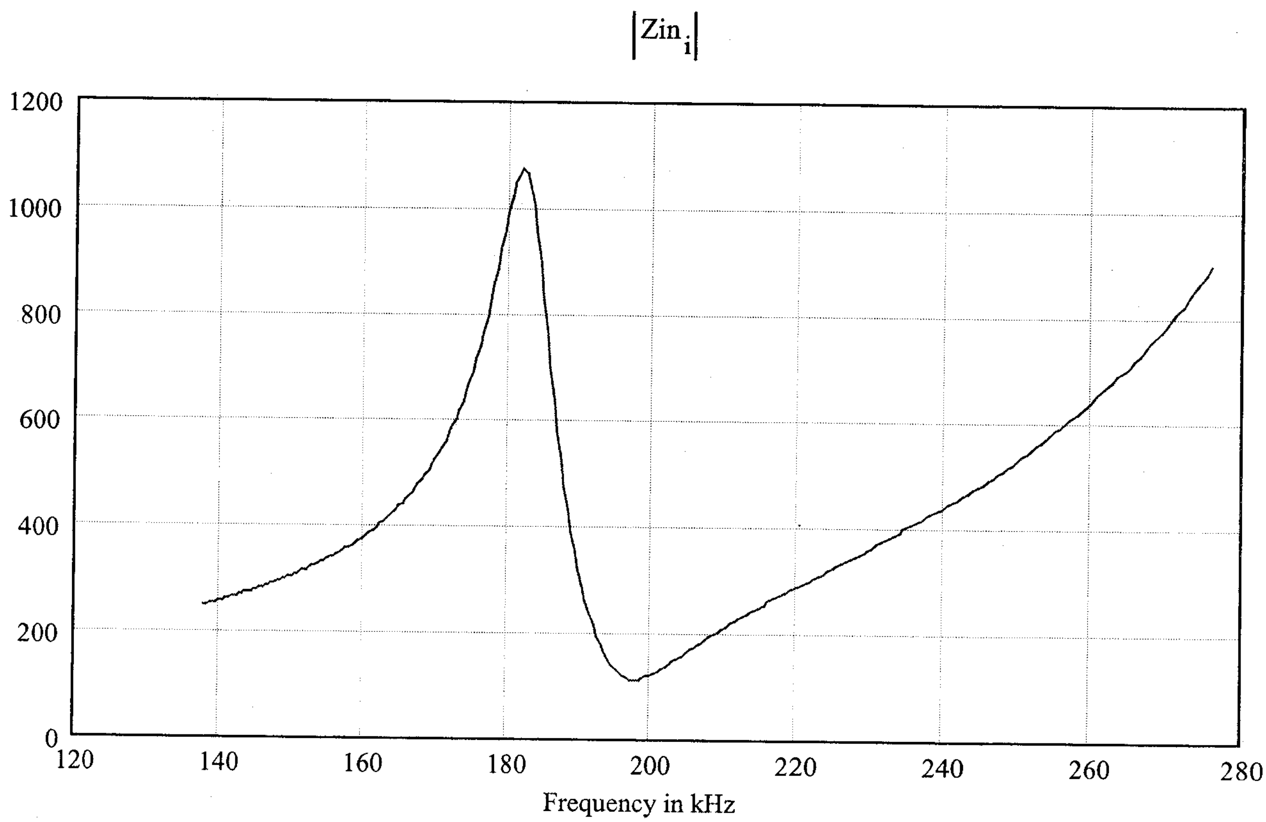

Figure 9c. Mathcad model

V. Performance Measurements:

Both prototypes were tested and calibrated in the Acoustic Open Tank Facility (OTF) at the Naval Undersea Warfare Center (NUWC) Division Newport. We chose this facility as it is the primary test facility for prototype acoustic evaluation of underwater devices. The OTF features a large shallow water facility with a fully automated data gathering system, and associated mechanical support equipment. Here the prototype acoustic characteristics were measured using NUWC's six channel Transducer and Hydrophone Acoustic Measurement and Evaluation System. Though more expensive, the NUWC test site was preferred over sonabouy tests because the facilities provided a more controlled and accurate data collection platform with which to measure the shallow water performance parameters of the EDM prototypes. At this facility we were able to map directivity patterns with 0.01° accuracy.

Transmitting Voltage Response (TvR) and Directional Response (DR) were measured in the frequency range of 150 kHz to 250 kHz at the water temperature of 18.3 degrees C and a test depth of 2.28 meters (22 kPa) (the approximate depth and pressure of manatee shallow water habitats). The TvR curves are presented for both devices in Figures 10 a & b. Impedance Magnitudes measurements with respect to frequency are presented in Figures 11 a & b. Corresponding Phase measurement are presented in 12 a & b., and Directivity Response patterns of each projector in horizontal and vertical planes are provided in Figures 13 a & b and 14 a & b.

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TRANSMITTING VOLTAGE RESPONSE

Florida Atlantic University Transducer Unit 1
Pressure at one meter per volt applied at end of transducer cable; Balanced
18.3° C 2.28 m (22 kPa)

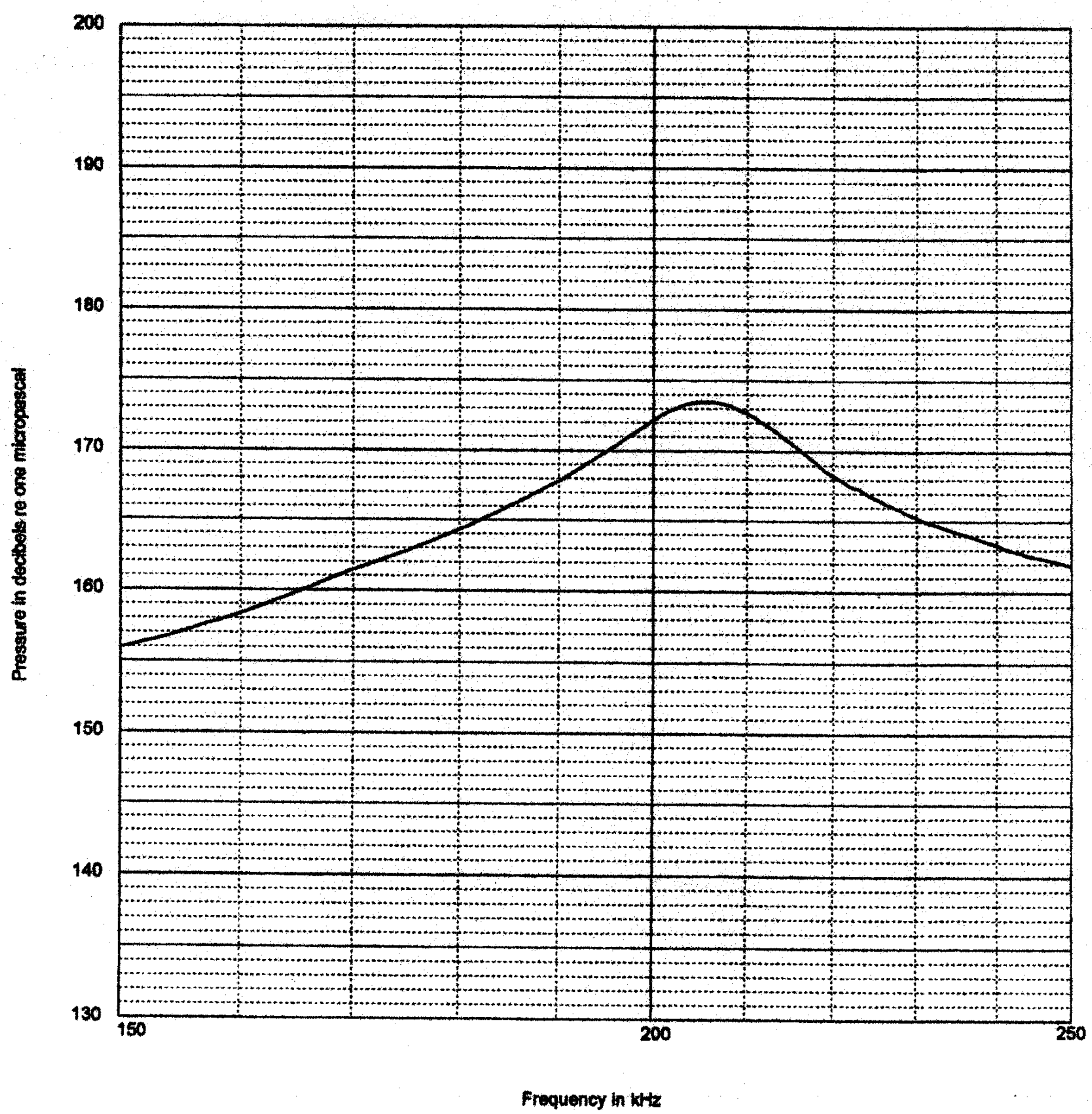

Figure 10a. Transmitting Voltage Response Curve (unit 1)

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SEPTEMBER 2003

TRANSMITTING VOLTAGE RESPONSE

Florida Atlantic University Transducer Unit 2
Pressure at one meter per volt applied at end of transducer cable; Balanced
18.3° C 2.28 m (22 kPa)

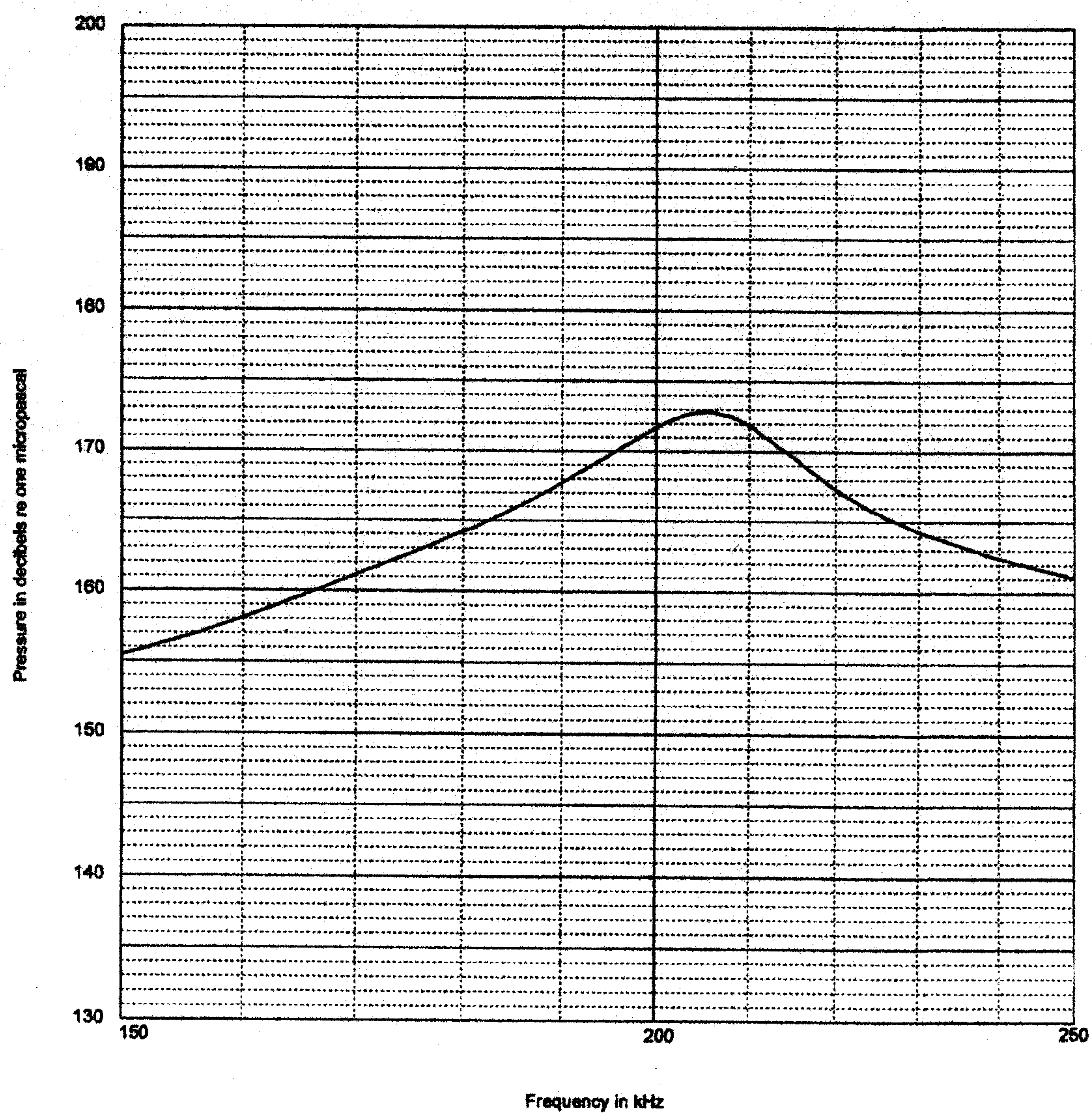

Figure 10b. Transmitting Voltage Response Curve (unit 2)

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IMPEDANCE MAGNITUDE

Florida Atlantic University Transducer Unit 1
Measured at end of transducer cable; Balanced
18.3° C 2.28 m (22 kPa)

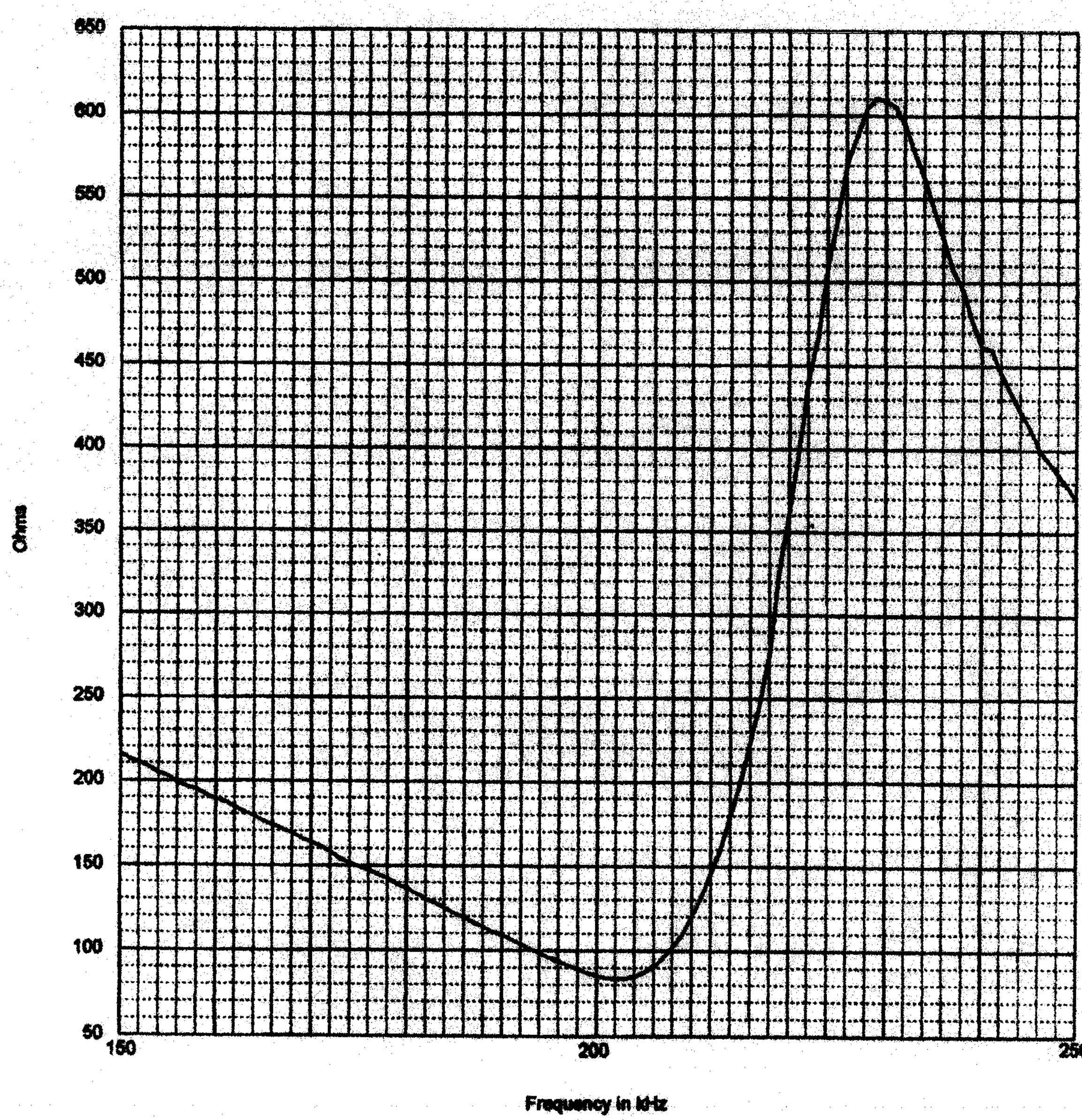

Figure 11a. Impedance Magnitude (unit 1)

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IMPEDANCE MAGNITUDE

Florida Atlantic University Transducer Unit 2
Measured at end of transducer cable; Balanced
18.3° C 2.28 m (22 kPa)

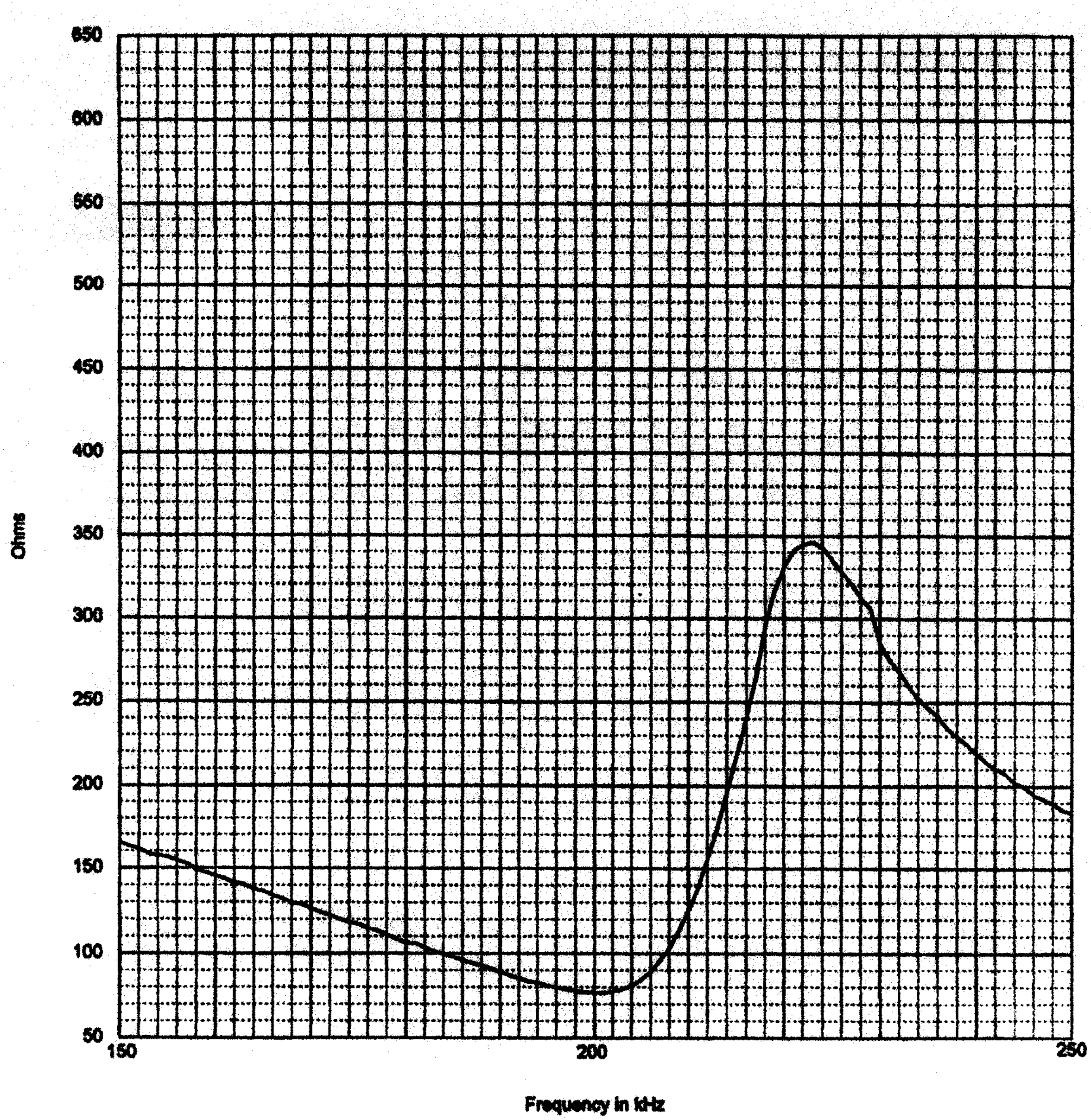

Figure 11b. Impedance Magnitude (unit 2)

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IMPEDANCE PHASE

Florida Atlantic University Unit 1
Measured at end of transducer cable; Balanced
18.3 °C 2.26 m (22 kPa)

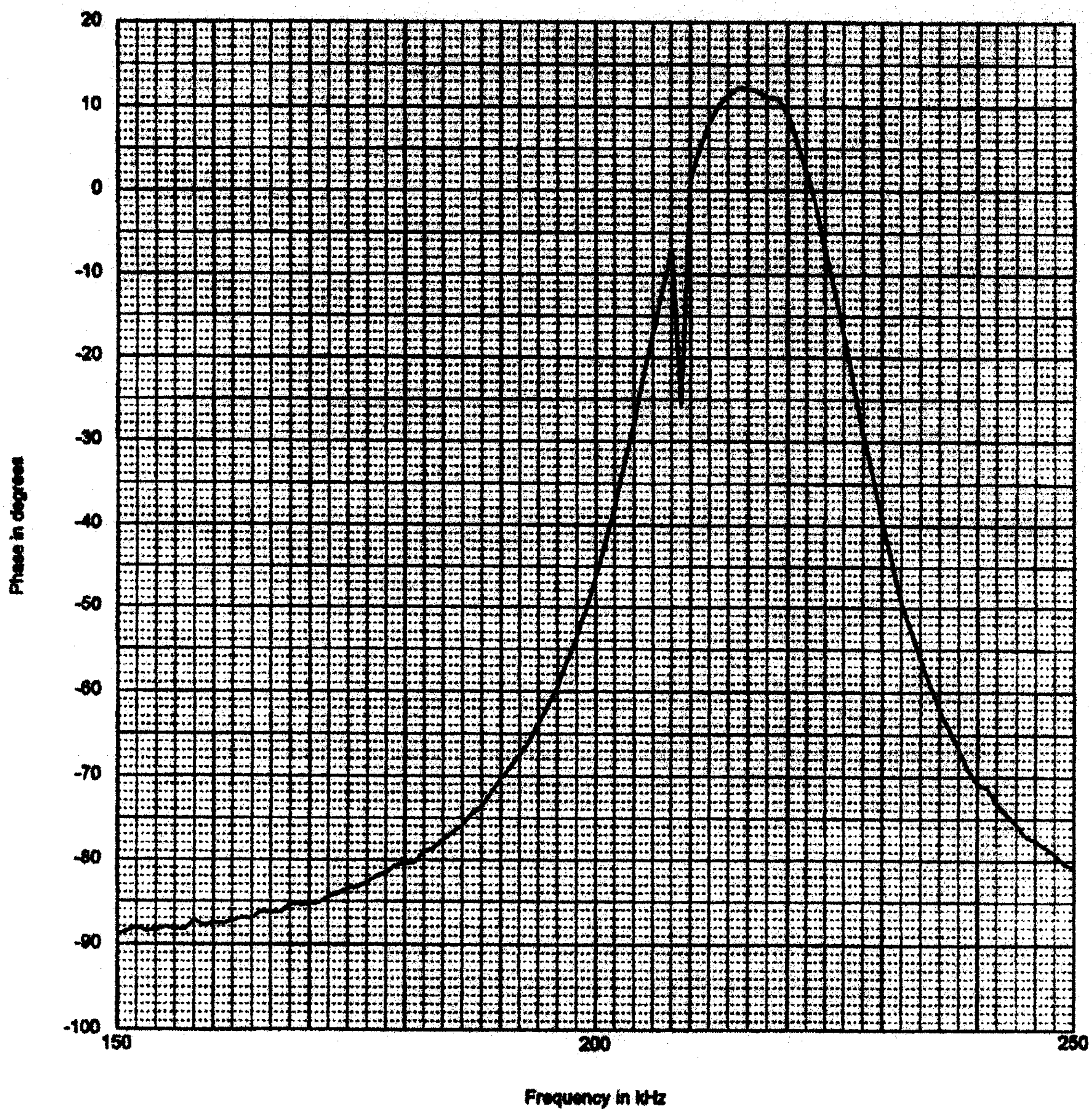

Figure 12a. Impedance Phase (unit 1)

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IMPEDANCE PHASE

Florida Atlantic University Unit 2
Measured at end of transducer cable; Balanced
18.3 °C 2.28 m (22 kPa)

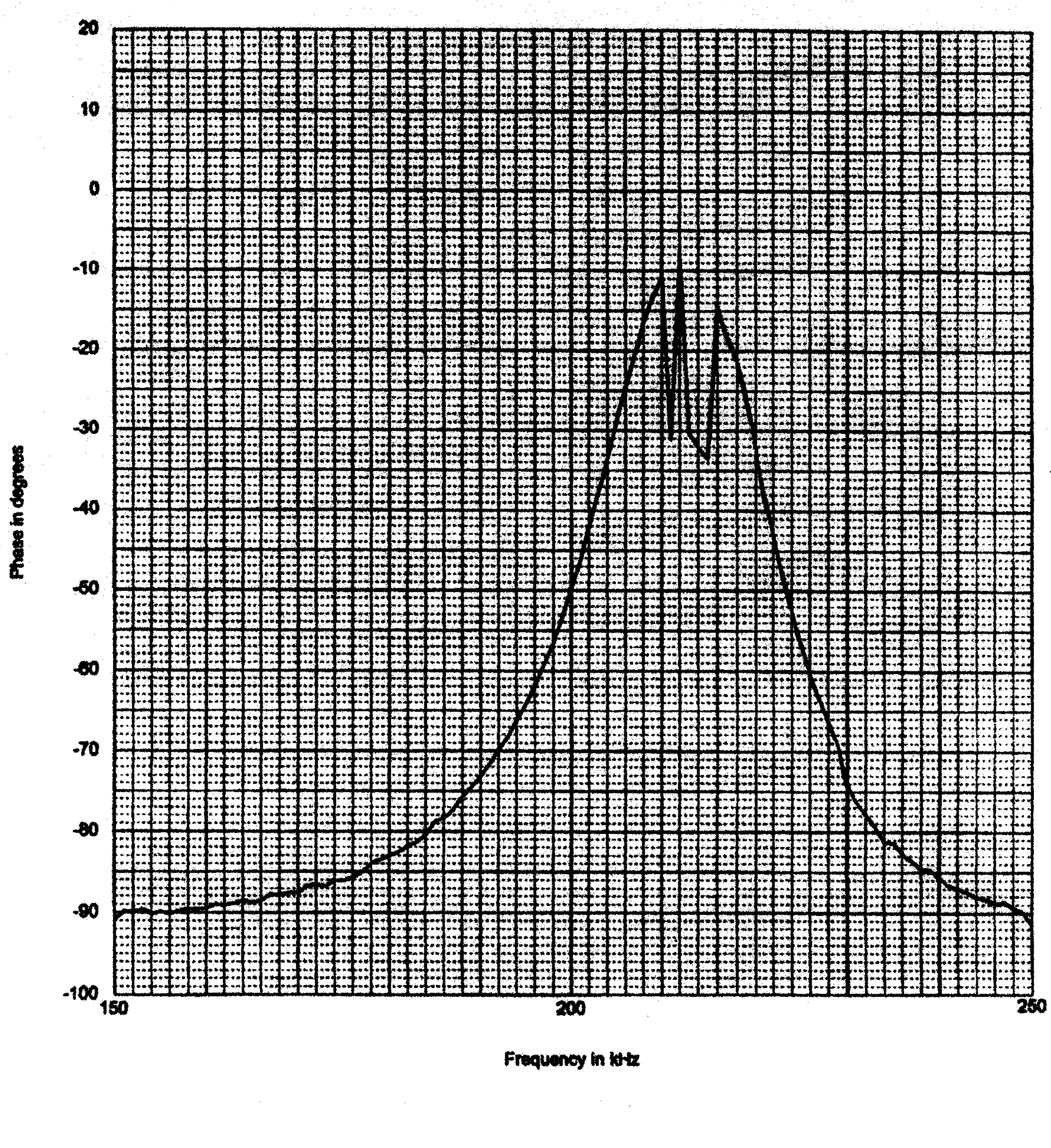

Figure 12b. Impedance Phase (unit 2)

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DIRECTIONAL RESPONSE

Florida Atlantic University Transducer Unit 1
Transmit
XY Plane
200 kHz
18.3° C 2.28m (22 kPa)

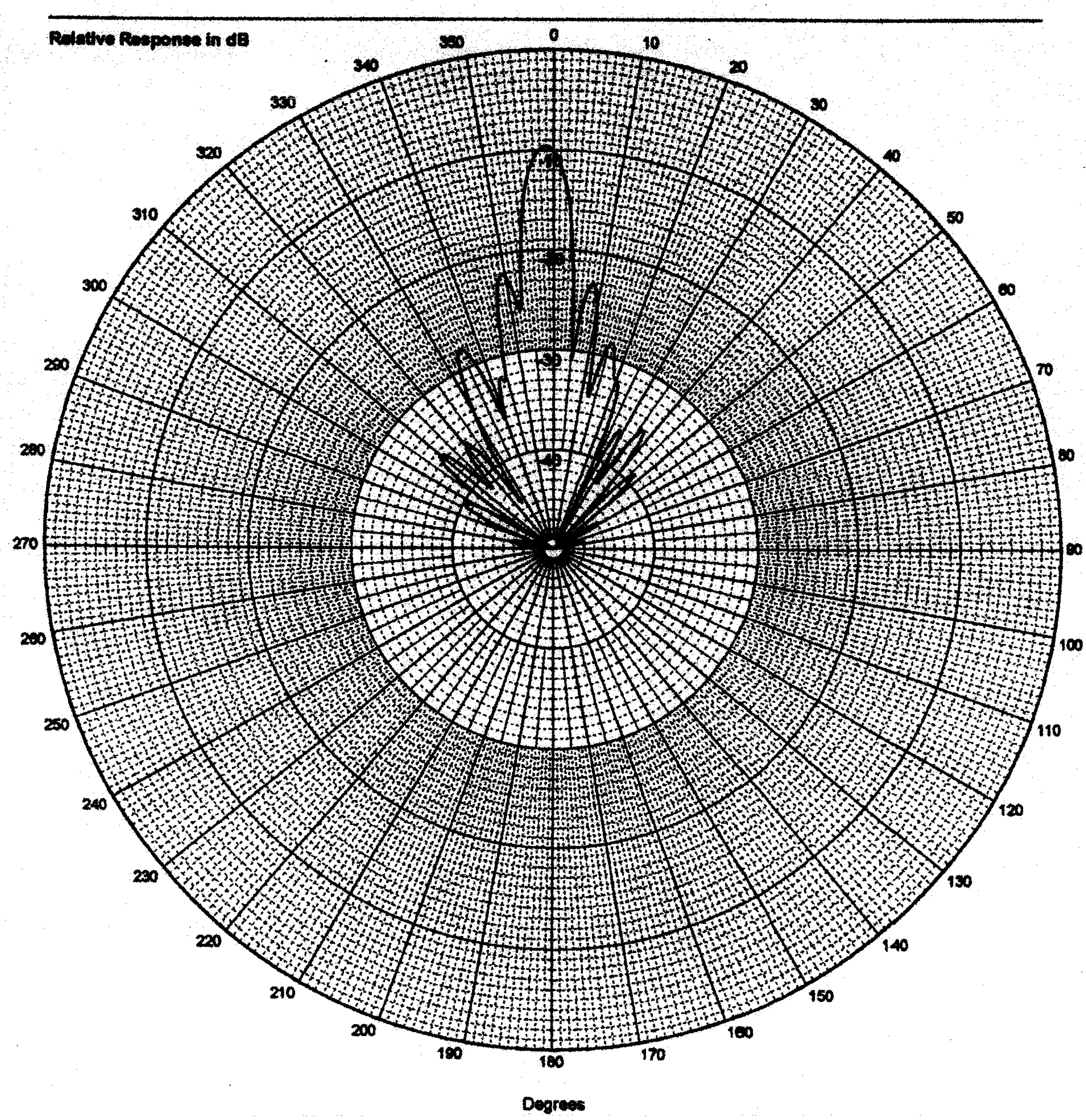

Figure 13a. Directional Response XY plane (unit 1)

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DIRECTIONAL RESPONSE

Florida Atlantic University Transducer Unit 2
Transmit
XY Plane
200 kHz
18.3° C 2.28m (22 kPa)

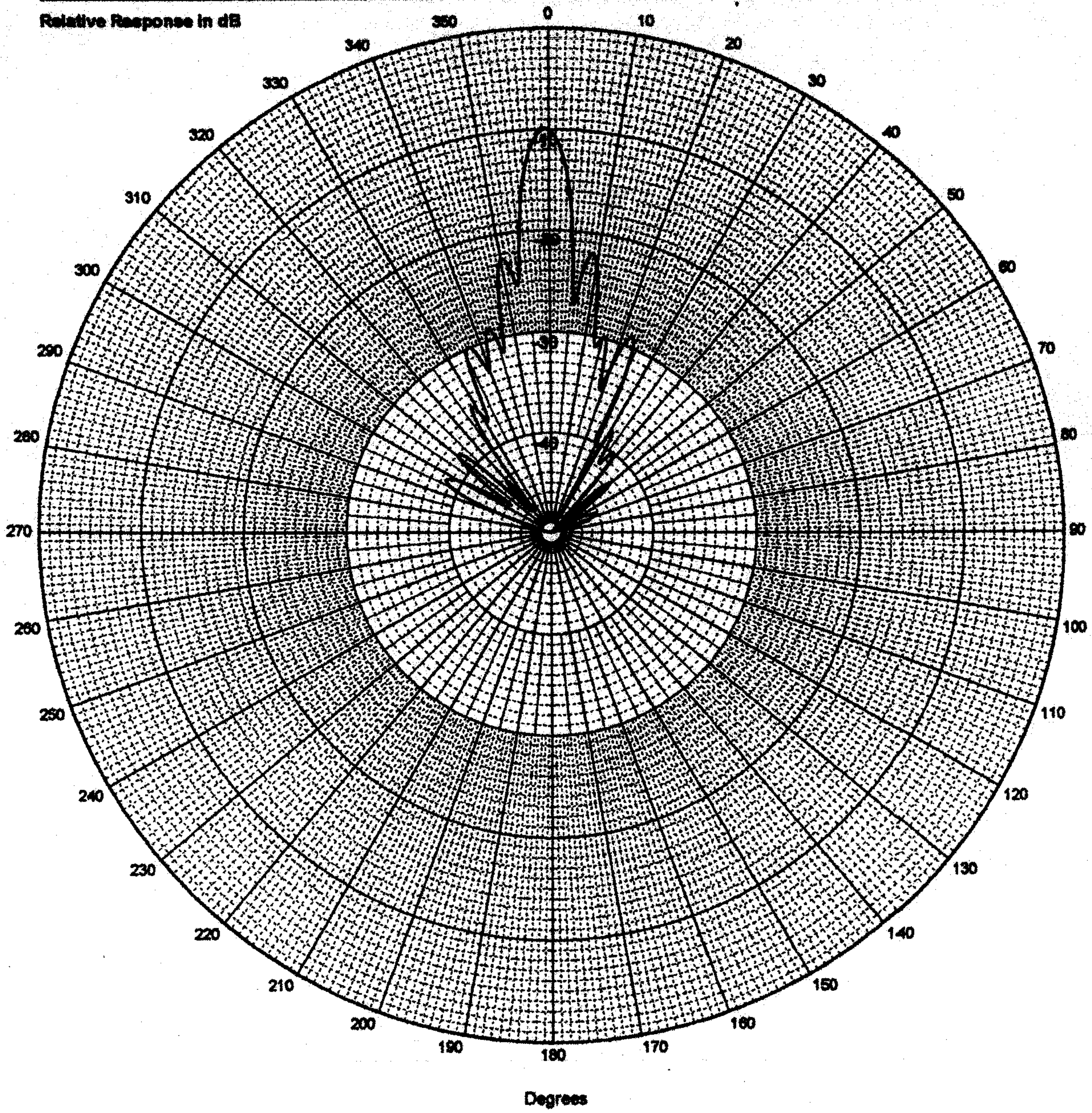

Figure 13b. Directional Response XY plane (unit 2)

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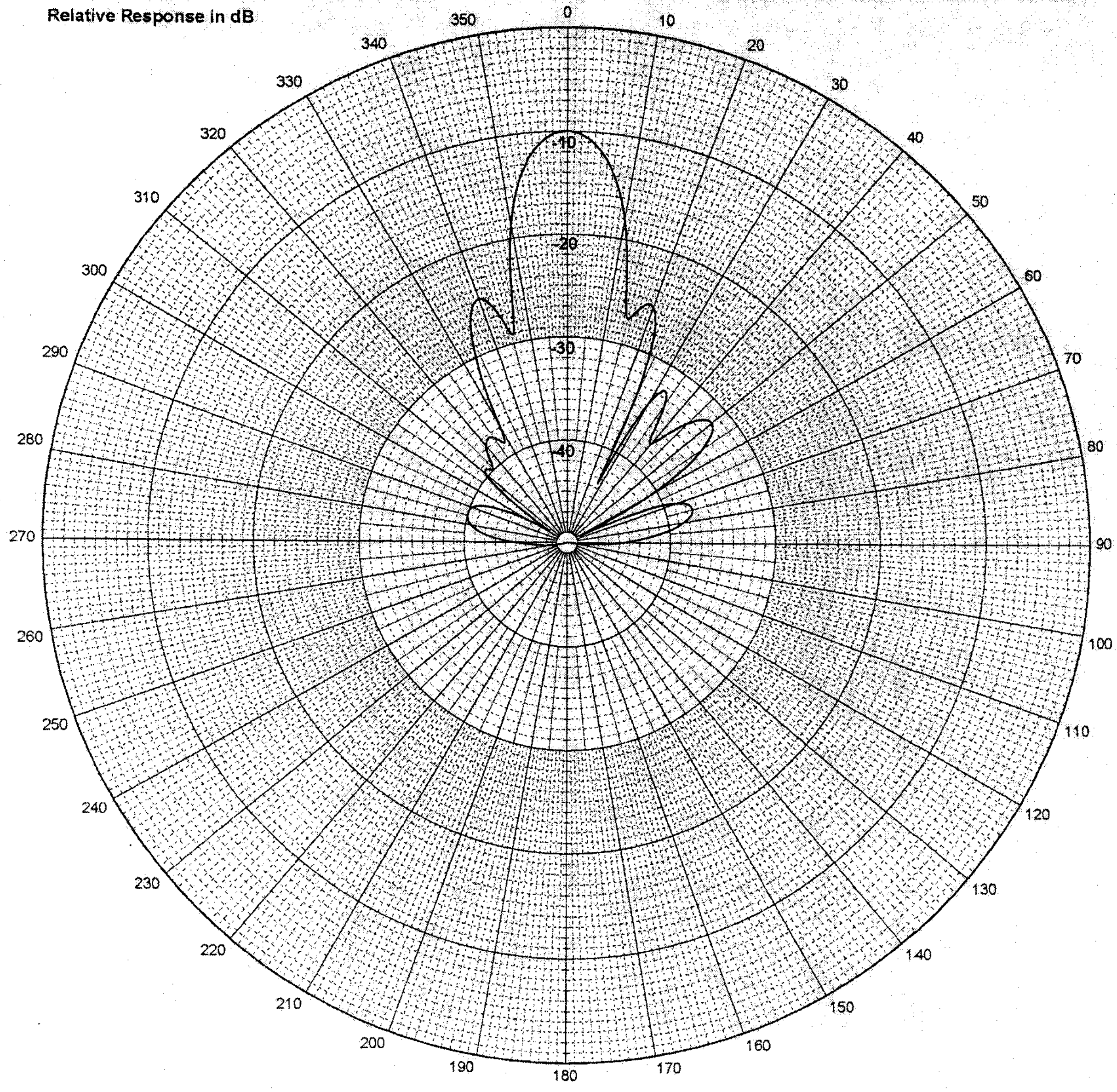
DIRECTIONAL RESPONSE

Florida Atlantic University Transducer Unit 1
Transmit
XZ Plane
200 kHz
18.3° C 2.28m (22 kPa)

Relative Response in dB



Degrees

Figure 14a. Directional Response XZ plane (unit 1)

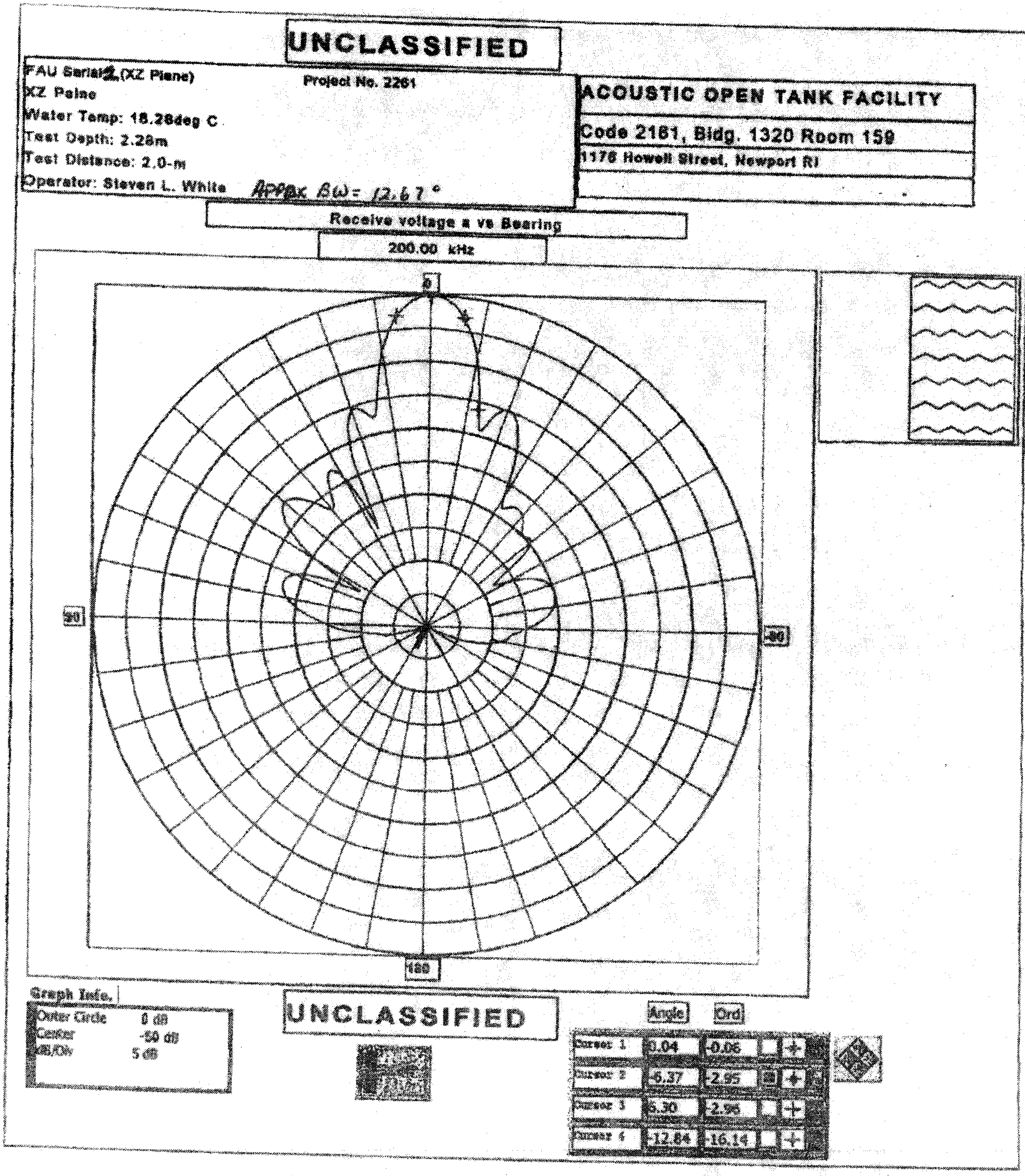


Figure 14b. Directional Response XZ plane (projector 2)

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USRD DRAWING 62785
(REVISED 1 AUGUST 1995)

COORDINATE SYSTEM FOR TRANSDUCER OR PANEL ORIENTATION

The left-handed coordinate system in the sketch below is affixed to the transducer or panel and moves with it, regardless of its physical position. The angle (θ,ϕ) denotes the direction of sound propagation. Measurements are made with sound propagated parallel to the positive X axis (θ=90°, ϕ=0°) unless otherwise specified.

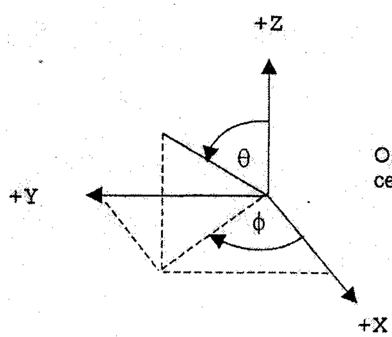
For some measurements, the position of an auxiliary transducer may be specified in terms of cartesian coordinates X, Y, and Z.

Transducers and panels are oriented as follows:

ACOUSTIC SURFACE	ORIENTATION
Cylinder	The cylindrical axis is the Z axis; a reference mark for the +Z direction and for another axis is specified.
Plane	The plane or piston face is the YZ plane, with the X axis normal to the face at the geometric center. A reference mark in the YZ plane is specified.
Sphere	Points on the surface for any two of the three axes are specified.
Other	A sketch of non-conforming configurations is provided.

Directional Response Patterns: Unless otherwise specified, the following apply:

		POSITION OF AXES OR DIRECTIONS ON POLAR PLOTS				
SPECIFIED PLANE	AXIS OF ROTATION	+X AXIS	+Y AXIS	+Z AXIS	θ=45° ϕ=90°	θ=45° ϕ=270°
XY	Z	0°	90° CW	Upward	-------------	-------------
XZ	Y	0°	Downward	90° CW	-------------	-------------
YZ	X	Upward	0°	90° CW	-------------	-------------
ROLL	θ=45° ϕ=270°	0°	-------------	-------------	90° CW	Upward



Origin is at assumed acoustic center of transducer or panel.

The parametric output (difference frequency) was effectively filtered with the predicted difference frequency output. The signal showed the distinct arrivals of the parametric energy at the times predicted by the geometry of the test area and transducers. The hydrophones used to measure all signals had a sensitivity of –220 dB over the frequency range specified.

The parametric effect is clearly shown, including the (more or less) expected frequency dependence (dependence is between ω and ω^2). Based on the way the parametric effect scales with drive (voltage^2), a drive of 100 volts in each primary should produce an additional 14 dB of output.

VI. Discussion:

The manatees' most sensitive range of hearing and localization is 10 – 20 kHz. We selected 15 kHz as a center frequency to alert manatees since it falls in the trough of the manatees best hearing and localization abilities. MADs must be highly directional to enable manatees to effectively locate approaching boats. A 6° vertical and 12° horizontal beamwidths were chosen to insure the alarm is only detectable when the manatee is in a specific boat's direct path, and in imminent danger of being hit, and to also allow for the variable pitch of a boat underway.

The directionally insures against habituation that can otherwise occur with omnidirectional sounds, that while readily heard, have no temporal consequences for the listener. In a linear projection mode the aperture required to produce such a narrow 6° horizontal beam is 8.5 wavelengths or 34 inches. The vertical beamwidth of 12° requires is a 17 inch aperture. Clearly a 34 x 17 inch aperture is too large and would create significant drag for most recreational boats. The desired beamwidth are achieved using a much smaller projector and relying on the nonlinearity of water to produce a virtual volumetric end-fired array in the water. In order to use parametric acoustic projection, we pick a carrier frequency, f_0, and a signal and heterodyne the signal up to a center frequency, f_c, such that $|f_c - f_0| \sim 15$ kHz. Using this procedure, we require a projector that is about 2.6- x 1.3-inches to produce a 6° horizontal x 12° vertical beam centered at 200 kHz. To achieve maximum parametric energy in the desired 10 to 20 kHz band, we chose to use single side-band signals. The details of how we achieved this are included in the previous sections along with calibration measurements. The equations and insight into source levels and beam patterns can be found in APPENDIX A.

The beam pattern for parametric project can be visualized by taking the product pattern of the 2 primary beam patterns and convolving them with that of the Rutherford beam pattern derived by Westervelt. That gives one a quick estimate on the beam pattern at difference frequencies. Source levels are easy to calculate using Equation (9) from APPENDIX A.

Equation (9) is preferable to Equation (10) because some sound pressure levels must be used for levels in the interaction zone where the spherical spreading range has not been reached. In the interaction zone, levels decrease as ~3 dB per distance doubled rather than 6. The slower rate of decrease is advantageous in achieving sound pressure levels manatees can hear.

The Directional Response curves show we have achieved beamwidths on the two prototypes of 5.62° in the xy-plane and 12.8° in the xz-plane which is within our design parameters. The 3-dB bandwidth of the projectors is 195 to 213 kHz, close enough to the 20 kHz bandwidth specified to allow us to input signals with bandwidths suitable for the alert signals. The baseband signals will be heterodyned up to the projector bandwidth as shown in the block diagram of the system in Figure 1. When mixed with the constant high-frequency sinusoid, both sinusoids are projected into the water. The water provides the nonlinear medium that will heterodyne the signal down to f^2 x the baseband signal. In signal design the $^1/f^2$ is equivalent to a double differentiation.

The Impedance curve at the 3-dB band is approximately 78 to 80 ohms. That with the transmitting voltage response (TvR) curve shows we need approximately 100 volts at the projector input to achieve a 210-dB source level and 300 volts for a 220-dB level.

Calculations for safe drive levels were done using an Engineering Acoustics proprietary program. These calculations indicate that projector heat tolerances can be exceeded if driven above a 25% duty cycle at the 220-dB level. However, the Impedance Magnitude and TvR data confirm the devices can be driven at 210 dB at the 100% duty cycle with no risk of overheating. While the small projectors can handle the heat load at 100% duty cycle, we will not use over 50% duty cycle in our signal designs. The parametric outputs and bandwidth provide sufficient power to alert manatees without the risk of overdriving the projectors.

The required levels to be projected in the wild depend on ambient noise levels, manatee reaction time, critical ratios (CR), signal propagation and the speed of an approaching boat. In the 10- to 20-kHz bandwidth, ambient noise can routinely average 75 dB re 1 μPa in estuarine and marine manatee habitats. The prominent contributor to the noise in this bandwidth is snapping shrimp. The parametric output needs to account for the ambient noise level and the manatees' minimal Critical Ratios, along with the speed of the boat, maximum propagation loss with distance, and the amount of time a manatee requires to react. The perception that manatees are lumbering and slow is not entirely true. While reaction times are not well documented for manatees, we know that when startled or frightened, manatees can react instantaneously, with bursts of power and can move 15 MPH or 22 ft/sec [19, 20]. If alerted 3 sec before an approaching boat arrives, a manatee could conceivable move 66 ft. However, a manatee might require 2 sec or more to first perceive the threat before cognitively reacting. For discussion we will assume manatees require a minimum 5 sec warning in order to react and safely avoid approaching boats. For a boat traveling 25 MPH the MAD would then need to project the alarm to 183 ft (56 m) ahead of the boat. Propagation loss for 56 m is 35 dB for spherical spreading or 17 dB for cylindrical. Parametrically produced sound in water propagates with a 3-dB loss while inside the interaction zone. The interaction zone is defined as the point of 3-dB absorption for the primary frequencies. Consequently, we require a signal strength of 75 dB + 17 dB + some critical ratio (CR) for the alarm signals or 93 + CR for the manatee to hear the projected signal. In addition to defining signal components and measuring associated CR's for tonals we have also measured masked thresholds and associated CR estimates for various noise bandwidths and controlled playbacks of manatee vocalizations, and boat noise approach sequences.

The minimal projected level needed for a manatee to detect a vocalization would be 88 since the (CR) for vocalizations has been measured at (-5 dB). For broadband fast-boat approach signals, the CR can be as low as (9) so a minimum of 102 dB re 1 μPa would be needed. Critical ratios for pulsed-FM slides vary from –2 to 2 dB above ambient, making them candidate signals for alerting manatees with the MAD projections. Minimum levels would be 91 dB re 1 μPa. Using FM slides alone would require that manatees learn to associate these noval sounds with boats. However, using them with select boat noise sequences would produce a sound that manatees may immediately recognize as threatening and associate quickly with boats.

The output level for parametric projection increases with frequency for a constant input ($P \sim f^2$) As discussed, in signal design (f^2) is equivalent to double differentiation of a linear base-band signal.

In mid 1940 S. O. Rice at the Bell Telephone Laboratory was experimenting with human speech for minimizing the bandwidth necessary for understandable telephone communication [21]. He found speech to be clearly understandable and the speaker identifiable if recorded speech were double differentiated and hard clipped and then played into a telephone receiver. We believe the double differentiation of parametric signals by the water medium would not affect the ability of any mammals including manatees to recognize the origin of any familiar sound played back from 10 to 20 kHz through the MAD. Therefore we can incorporate boat noise into the MAD so manatees might immediately recognize the threat. We can also accommodate for the double differentiation by double integrating, multiplying the recorded boat noise by f^2 before playing it through MAD.

VII. Summary:

Engineering Acoustics Inc, (EAI) in Orlando Florida built two systems to the design specifications of Dr. Joseph Blue. The circuit design was done by EAI and assembled in South Africa and the thickness mode resonance projectors were constructed at EAI in Orlando. These prototypes incorporate all the electronic circuitry, amplifiers, and signal generators into a small light weight watertight package that goes onboard and is powered by the boat's 12-volt battery or a suitable alternative. The control boxes have not been machine molded or streamlined for marketing appeal. We have purposely kept the system boards accessible so we can elect to monitor outputs and make adjustments over time. The projectors are designed for through-the-hull or transom mounting devices. They are rugged units capable of withstanding large hydrodynamic forces on the hulls of recreational and commercial vessels.

Parametric output, impedance magnitude, phase, transmitting voltage and directional response measurements demonstrate that these parametric projectors meet all specifications. Test calibrations further confirm we have adequate systems with good high-frequency projectors. The small systems can operate at 100% duty cycles at optimum bandwidths without the risk of overdriving the projectors. The MAD prototypes can incorporate input signals that manatees may already associate with danger such as propeller cavitation noise. This may negate the need for manatees to undergo any conditioning to associate completely novel alert signals with boats. The most economical route for designing and fabricating just two prototypes was to build analog based systems. The cost for two digital systems was prohibitive. With the circuitry developed, future larger production could now be accomplished economically with digital components. Depending upon the size of a production run, the estimated cost for commercial manufacturing could be less than $200 per unit. The costs for each unit would be incurred by the end user, and not by the general public. The unit costs could be lower than most fish and depth sounders. If MAD's prove to be effective in alerting and in protecting manatees, they would be the most share based affordable and only technological solution that reduces the incidence of collisions with both recreational and slower moving commercial vessels.

VIII. Recommendations:

We recommend the controlled testing of these MAD prototypes with wild manatees and recreational boats as proposed in our USFWS permit application and 1997 reports to the Florida Department of Environmental Protection. We also propose that limited real world applications of the MADs for slow moving barges be initiated. We have demonstrated that the acoustic shadows in font of barges are profound and the condition should be mitigated to protect manatees. We have proposed inputting modulated ship noise [1,3] to "fill in" these shadows so that manatees will have some warning of their approach, and not be confused or seek refuge in the quiet shadows ahead of these vessels. Slow speed regulations do not address this concern and are ineffectual in this regard, as these vessels are already going slow.

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