SURTASS LFA HIGH FREQUENCY MARINE MAMMAL MONITORING (HF/M3) SONAR: System Description and Test & Evaluation

26 November 1999
(Revised November 2001)

Prepared by:

William T. Ellison, Ph.D.
Marine Acoustics, Inc.

Peter J. Stein, Ph.D.
Scientific Solutions, Inc.

Under U.S. Navy Contract
N66604-98-D-5725

Table of Contents

Table of Contents (continued)

List of Figures

List of Figures (continued)

List of Tables

Acronym List

A/D	analog to digital
AG	array gain
APTF	Acoustic Pressure Tank Facility
BL	beam level
BW	bandwidth
CAD	computer aided design
CFAR	constant false alarm rate
COTS	commercial off-the-shelf
CPA	closest point of approach
dB	decibel
DI	directivity index
DSP	digital signal processing
DT	detection threshold
EIS	environmental impact statement
EVA	environmental acoustics
FA	false alarm
FAR	false alarm rate
ft	foot
FM	frequency modulated
FOM	figure of merit
GPS	global positioning system
GRP	glass reinforced plastic
HESS	High-Energy Seismic Surveys
HF	high frequency
HF/M3	High Frequency Marine Mammal Monitoring
Hz	Hertz
kHz	kiloHertz
kph	kilometers per hour
kt	knots
LFA	Low Frequency Active
LFS SRP	Low Frequency Sound Scientific Research Program
LOS	line of sight
LTS	LFA Transmit System
m	meter
MILDET	military detachment
MFO	matched-filter output
msec	millisecond
M/V	motor vessel
MZ	mitigation zone
μPa	micro Pascal
NFESC	Naval Facilities Engineering Service Center
NL	noise spectrum level
nm	nautical mile

Acronym List

NSMRL	Naval Submarine Medical Research Laboratory
NUWC	Naval Undersea Warfare Center
OEIS	overseas environmental impact statement
OEM	original equipment manufacturer
PC	personal computer
PD	probability of detection
PDF	probability density function
PE	parabolic equation
PG	processing gain
PL	pulse length
PPI	plan position indicator
psi	pounds per square inch
R/V	research vessel
RHIB	rigid hull inflatable boat
RL	received level
rms	root mean squared
S/R	source/receiver
SACLANT	Supreme Allied Commander, Atlantic
SE	signal excess
SL	source level
SNR	signal-to-noise ratio
SOC	SURTASS Operations Center
SSI	Scientific Solutions, Inc.
SURTASS	Surveillance Towed Array Sensor System
SVP	sound velocity profile
TD	time signal duration
TL	transmission loss
TMA	time motion analysis
TS	target strength
TVR	transmit voltage response
UHF	ultra high frequency
VHF	very high frequency
VLA	vertical line array
WF	waveform
WT	wavetrain
yd	yard

Acknowledgements

This work was financially supported by the United States Navy under contract N66604-98-D-5725. The University of North Carolina, Department of Marine, Earth and Atmospheric Sciences provided technical and editorial support.

EXECUTIVE SUMMARY

Abstract - ***The High Frequency Marine Mammal Monitoring (HF/M3) sonar system was specifically designed to meet the marine mammal mitigation plan proposed by the Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Environmental Impact Statement. The system is integral with the SURTASS LFA sonar, residing at the top of the vertical transmit array, utilizes PC-based processing and control, and is comprised primarily of commercial off-the-shelf (COTS) components. The HF/M3 is an active sonar operating in the 30 to 40 kHz frequency range. The system utilizes four independent transducers mounted on a rotating carousel. Each transducer consists of an omni-directional hydrophone located at the focal point of a 31 x 46 cm air-backed, parabolic reflector. The reflector provides for an on-axis transmit and receive directivity factor of 20 to 25 dB. The system has been tested in numerous field trials, where its ability to detect marine mammals of various size has been qualitatively verified. Quantitative performance estimates, generated using empirical interference and target echo models, suggest that a single, moderately sized (~10 m in length) marine mammal swimming radially toward the system has a probability of being detected before entering the LFA mitigation zone (180-dB sound field) approaching 100 percent.***

INTRODUCTION

The Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) sonar meets modern anti-submarine warfare requirements by improving capabilities to detect quiet diesel submarines at stand-off ranges. It consists of a low frequency active sonar transmitter hung below a SURTASS ship and uses the SURTASS passive towed array as the receiver. Despite the system's demonstrated capabilities, concerns over LFA's potentially harmful acoustic effects on marine mammals have delayed deployment until completion of environmental studies and regulatory compliance requirements.

The SURTASS LFA Sonar Environmental Impact Statement (EIS) has proposed the cessation of active transmissions from the system when a marine mammal closes within a specified annulus of received pressure level (180 dB re 1 μPa_{rms}) as a mitigation option. Through nationwide workshops and studies, such as the Low Frequency Sound Scientific Research Program (LFS SRP), biological experts have agreed to specify a mitigation zone surrounding LFA, which under most conditions is as shown in Figure 1. The only way for the SURTASS LFA system to avoid exposing marine mammals to the high sound pressure levels within this zone under all weather conditions and for vocalizing as well as non-vocalizing animals is with an active detection system.

To fill this mitigation role, the Navy has designed and fabricated the active High Frequency Marine Mammal Monitoring (HF/M3) sonar system. The system has been tested in field trials, where its ability to detect marine mammals of various sizes has been qualitatively verified. Quantitative performance estimates, generated using empirical interference and target echo models, indicate that a single, moderately sized (~10 m in length) marine mammal swimming radially toward the system has a probability of being detected before entering the LFA mitigation zone (180-dB sound field) approaching 100 percent.

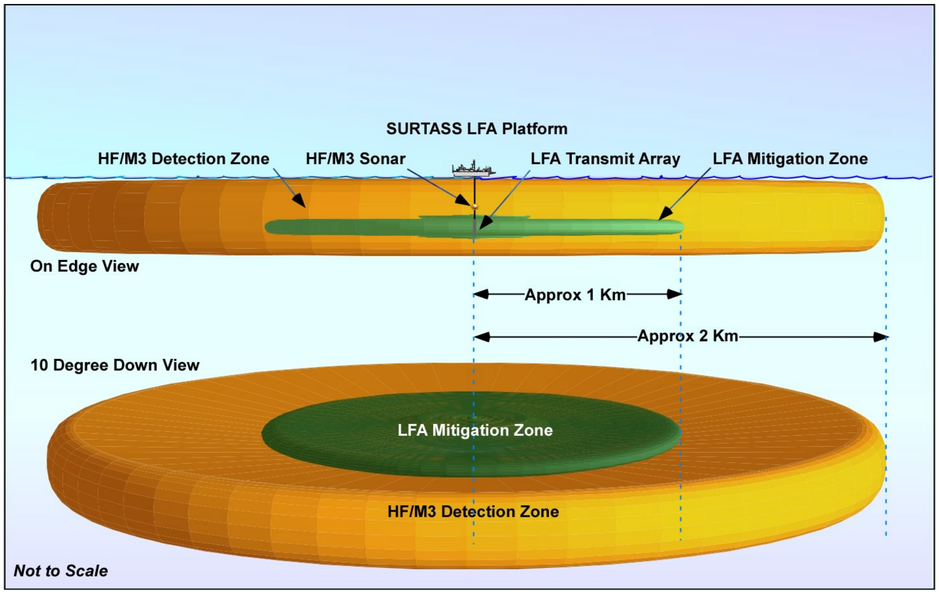


Figure 1. LFA marine mammal mitigation zone under most environmental conditions.

SYSTEM DESCRIPTION

The HF/M3 system was developed due to the lack of existing active high frequency systems that meet the requirements for this application. An essential objective of the HF/M3 design was to have the system wholly PC-based using commercial off-the-shelf (COTS) components and software throughout. This provides not only reduced procurement and support costs, but also allows for rapid enhancement of system capability as more powerful COTS products become available.

Based on the mitigation requirements of SURTASS LFA sonar, the foremost design attribute of the system is its detection range (which exceeds the mitigation range by a factor of two under normal operational conditions.) The detection bearing of the animal must also be known but not to the degree of accuracy as the range. Eight-degree bearing sectors were determined to be more than adequate to not only detect the animal, but also to roughly track its progress relative to the LFA platform. At nominal detection ranges, the range rate and bearing rate on any detected animal will likely be quite high, and thus, a relative track will be readily apparent. This attribute of the detection geometry also facilitates an automated detection and tracking alert system. The system's operational concept is illustrated in Figure 2.

These objectives, along with the low required scan rate and moderate depth requirement (the nominal operating depth of the system is 80 to 200 m), led to the use of four independent, mechanically-steered transducers. This feature dramatically reduced the number of channels in comparison with a phased array-based system, thereby simplifying the system electronics and lowering the initial and maintenance costs.

The four independent, bi-directional (transmit and receive) channels are each comprised of an omni-directional hydrophone mounted in a parabolic reflector (see Figure 3). The reflectors provide 10 degree vertical and 8 degree horizontal half-power beamwidths and a one-way directivity index of 22 dB at 33 kHz. The transducer/reflector assemblies are mounted on a rotating carousel, which is stepped through the azimuth in 8-degree increments every 4 to 5 seconds, thus providing complete horizontal coverage every 45 to 60 seconds. Vertical steering capability allows adjustment of the acoustic beam to provide adequate coverage of the mitigation zone regardless of the local acoustic propagation environment. With tilt settings optimized for on-site refraction patterns, system performance is relatively insensitive to environmental factors, such as sea state.

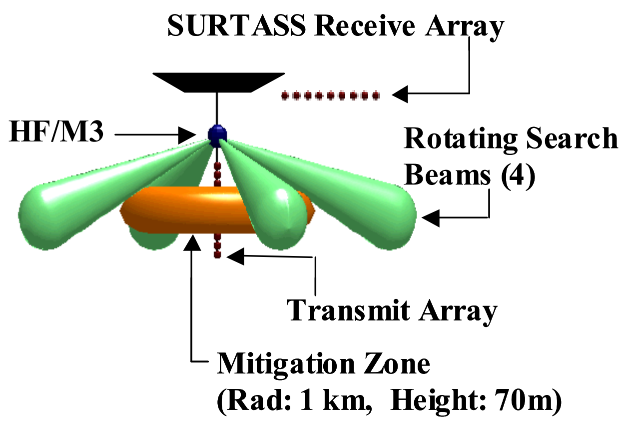


Figure 2. System concept schematic.

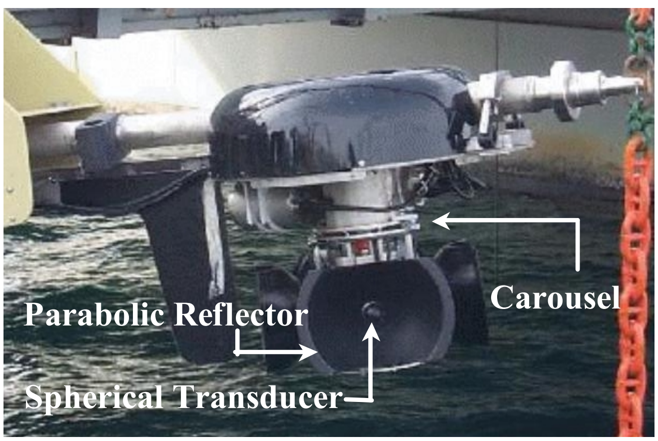


Figure 3. Detailed view of system without lower fairing being deployed at Naval Underwater Warfare Center (NUWC) sonar test facility, Seneca Lake, NY.

Local control is accomplished with an encapsulated computer system mounted within the interior of the towbody. Signal conditioning of echo returns is done by the towbody electronics package, including a time-variable gain amplifier and band-pass filter. A fiber-optic serial link provides RS-422 communications between the towbody system and the operator console topside, which performs detection signal processing and visualization. Table 1 summarizes system parameters.

Table 1. HF/M3 sonar system parameters

Transmit Frequency	30 to 40 kHz
Nominal Source Level	Variable up to 220 dB re 1 μPa at 1 m
Pulse Length	10 to 40 msec (nominal)
Repetition Rate	3 to 4 sec (nominal)
SL Ramp-up Period	5 minutes
Vertical Beamwidth	10 degree
Horizontal Beamwidth	8 degree
Vertical Steering	± 10 degree
Azimuthal sweep period	45 to 60 seconds
Directivity Index (one-way)	21 dB at 30 kHz 23 dB at 35 kHz 25 dB at 40 kHz
Detection Processing	Matched-Filter, Range-dependent Thresholding

The standard screen display at the operator's console provides a polar plot marking the range and bearing (similar to a conventional radar display) of echo returns that exceed predetermined detection threshold levels (see Figure 4). The graphic display can also show the ping-by-ping matched-filter output vs. range for the four independent channels. A toolbar at the top of the screen, along with pulldown menus allows the operator to set the operational parameters of the system. Additional toolbars allow the operator to mark and annotate the polar display to facilitate target tracking.

The system will nominally be deployed in deep water. As a result of the excellent side-lobe rejecting properties of the parabolic reflectors, under neutral (i.e., zero sound-velocity slope) surface layer conditions, interference is noise-dominated to ranges of approximately 400 m and surface clutter dominated in the 400 to 2,000 m range. Because the SURTASS LFA sonar predominantly operates in deep water, under normal operating conditions, the HF/M3 sonar should experience no interference associated with bottom reverberation.

The HF/M3 sonar and the specifications of its operating protocols were designed to minimize possible effects on marine animals. The operating procedures provide for the source level to be adjusted to ensure that received levels are below those that could potentially affect marine mammals or sea turtles if they approach the HF/M3 sonar.

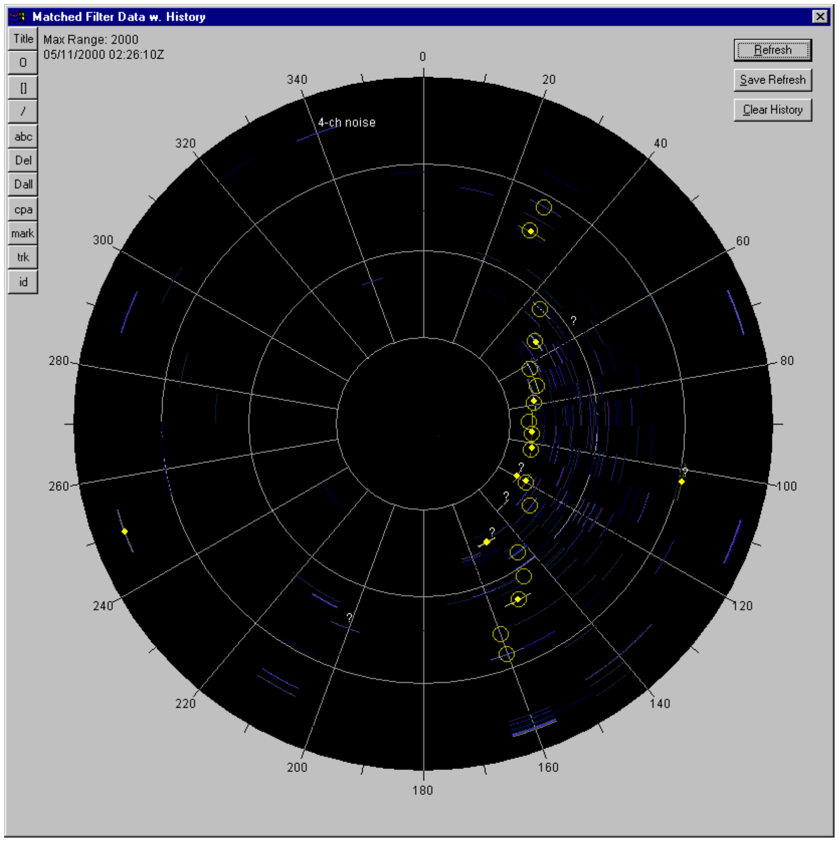


Figure 4. Polar display of HF/M3. The figure displays multiple detections of a small, artificial target drifting past the HF/M3 sonar.

PERFORMANCE CAPABILITIES

To satisfy the objective of the SURTASS LFA Sonar EIS, detailed analysis and quantitative predictions of system performance were required. System performance is determined by the probability that a marine mammal will be detected before entering the mitigation zone. This probability is dependent on several factors including the single-ping probability of detection, animal behavior, local acoustic conditions and the HF/M3 sonar scan rate. The single-ping probability of detection is defined as the probability of detecting an animal present within the HF/M3 scan beam as a function of range using an individual echolocation transmission. Single-ping probabilities of detection and false alarm rates estimated here are based on conservative models of interference and target echo signal statistics, which are derived from measured data. Figure 5 shows the single-ping probabilities of detecting various marine mammals as a function of range. Based on the scan rate of the HF/M3 sonar, most animals will receive at least 8 pings before entering the LFA mitigation zone. Based on this, the probability of a marine mammal being detected prior to entering the mitigation zone approaches 100 percent.

A dedicated experiment designed to verify the system's ability to detect bottlenose dolphins was conducted off the coast of San Diego in August 2000. Trained dolphins were commanded to dive to moored underwater objects with the HF/M3 system positioned 400 to 1,000 m away. The predicted detection rate for these exercises was estimated at approximately 80 percent (per dolphin dive cycle). The tests were conducted in shallow (300 m), downward-refracting waters with search zones nearer to the surface than normal operating conditions would dictate. Reduced clutter interference and the propensity for dolphins to travel in pods will increase the probability of detection under normal operating conditions.

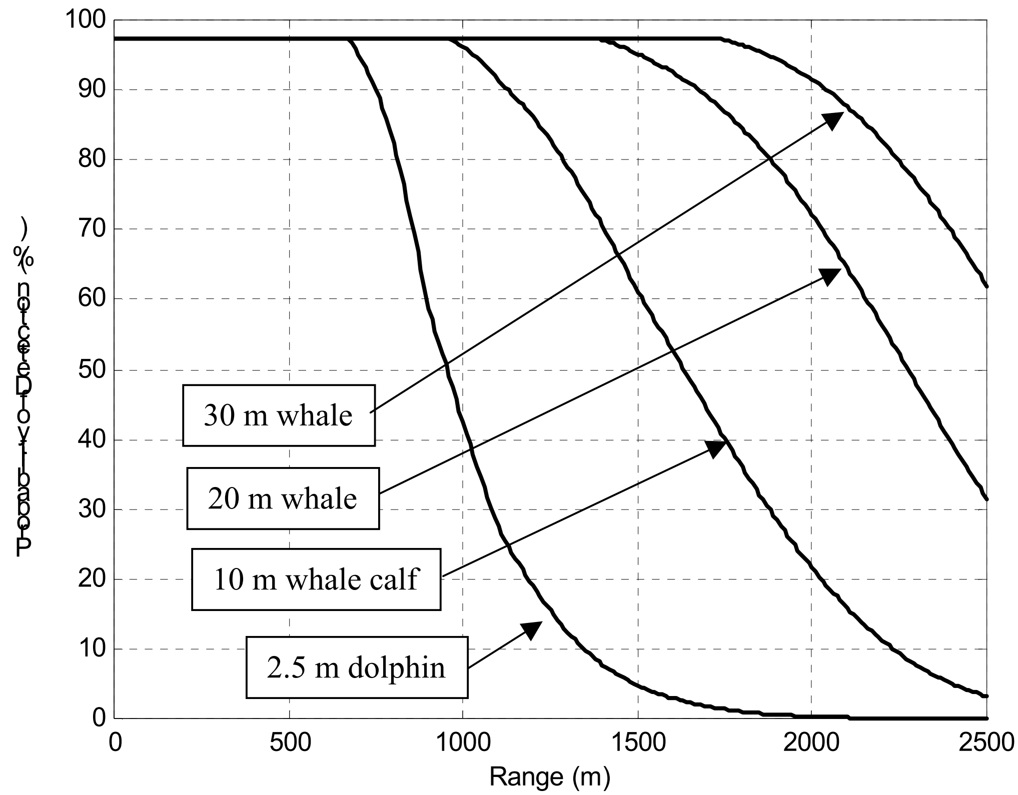


Figure 5. Predicted single-ping probability of detection for various animals.

A. SYSTEM REQUIREMENTS

1. <u>Background</u> - This report provides a description of the High Frequency Marine Mammal Monitoring (HF/M3) sonar system and its test and evaluation. The primary use of this system will be short-range detection of marine mammals in the vicinity of the Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) sonar source array for the purposes of mitigation.

a. <u>The Overall Requirement</u> - One of the mitigation options proposed in the SURTASS LFA Sonar Final Overseas Environmental Impact Statement/Environmental Impact Statement (OEIS/EIS)[1] is the requirement to shut down the active transmissions from the system when a marine mammal closes within a specified annulus of received power level of the source array. As explained below, the target for this mitigation level will be 180 decibels (dB) re 1 micro Pascal (µPa) (rms). In the past, SURTASS LFA sonar mitigation has been based on a combination of visual observations from the source vessel and acoustic tracking of vocalizing animals. Recent U.S. Navy sponsored Low Frequency Sound Scientific Research Program (LFS SRP) operations, which used the SURTASS LFA sonar system as a playback source, were conducted only during daylight hours, when visibility was good. However, normal SURTASS LFA sonar operations will also be conducted during periods of darkness and poor visibility, where this approach will no longer be adequate.

The specific received level (RL) of sound requiring mitigation has been an evolving topic within the regulatory community. Coincident with the timeframe of the LFS SRP test sequence, there have been several national-scale workshops conducted with the express purpose of addressing acoustic mitigation requirements.[2,3,4] It was the consensus of the assembled experts at these workshops that RLs of 180 dB re 1µPa (rms) marked the boundary at which higher levels might cause physical harm.[5,6] Factoring this new requirement into a practical mitigation standard requires that the SURTASS LFA sonar system shut down when animals are detected within, or clearly begin to approach, this 180-dB boundary. The only way for the SURTASS LFA sonar system to meet this requirement under all weather conditions, for vocalizing as well as non-vocalizing animals, is through some form of active detection system.

b. <u>Defining the LFA Mitigation Zone</u> - The LFA mitigation zone covers a volume ensonified to a level $\geq$ 180 dB by the SURTASS LFA sonar transmit array. Under normal operating conditions, this zone will vary between the nominal ranges of 0.75 to 1.0 km (0.40 to 0.54 nm) from the source array ranging over a depth of approximately 87 to 157 m (285 to 515 ft). (The center of the array is at a nominal depth of 122 m [400 ft]).

---

[1] "Final Overseas Environmental Impact Statement and Environmental Impact Statement for Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Sonar," Department of the Navy, Chief of Naval Operations, January 2001.

[2] "Mitigation Guidelines for High-Energy Seismic Surveys off Southern California," HESS Workshop Report of 12 June 1998, A. Knastner Ed., Mediation Institute, Pepperdine University, CA.

[3] NMFS Acoustic Criteria Workshop, 9-11 Sep 1998, Dr. Roger Gentry and Dr. Jeanette Thomas Co-Chairs.

[4] ONR Workshop on the Effects of Anthropogenic Noise in the Marine Environment, Dr. R. Gisiner Chair, Feb 98.

[5] The actual value discussed in the workshops was a range from 180 to 190 dB re 1µPa rms. The lower bound of 180 dB, therefore represents the more conservative figure from a safety viewpoint.

[6] Also see discussion in the SURTASS LFA Sonar Final OEIS/EIS (Footnote 1), on the selection of 180-dB level as the single ping upper value for the Risk Continuum.

The SURTASS LFA sonar mitigation zone and HF/M3 detection zone are illustrated in Figure A-1. Figure A-2 is a calculated projection for the sound field in the immediate near-field of the vertical line array (VLA).[7] Figure A-3 expands the sound field into the far-field region with a parabolic equation (PE) model projection.

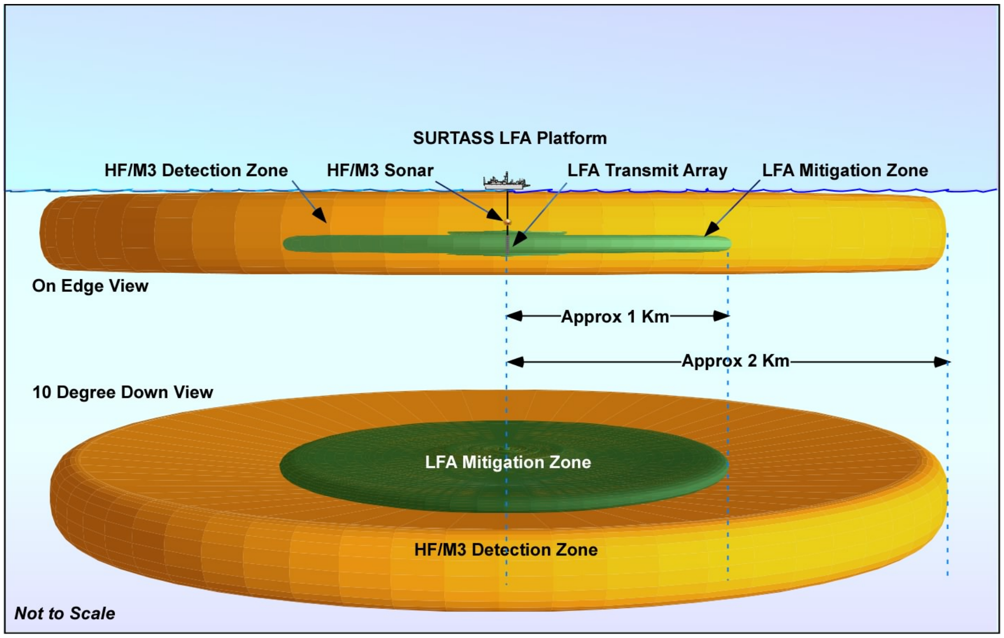


Figure A-1. HF/M3 Sonar Detection and LFA Mitigation Zone.

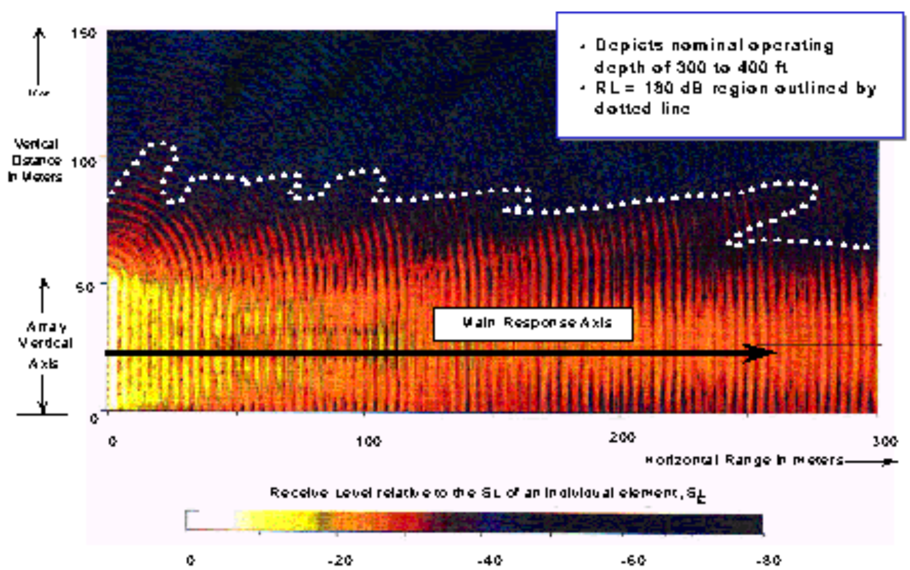


Figure A-2. Transmitted Near Field Sound Levels From a Low Frequency Multi-Element VLA.

7 W.T. Ellison, "Analysis of the Near Field Effects for a Vertical Line Array Source," MAI Tech Memo dtd 24 Oct 1996.

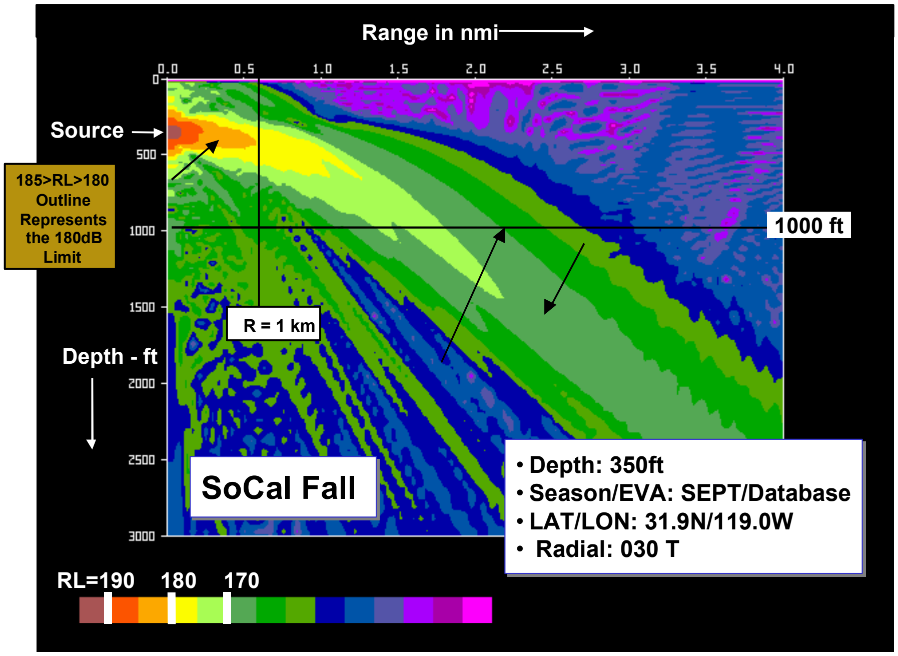


Figure A-3. PE Run for the LFA Array.

As this region is completely at depth, the only means by which marine mammals can be detected with near 100 percent confidence is by using a high frequency (f > 30 kiloHertz [kHz]) active sonar, similar in source level (SL) and capabilities to those used for finding fish and mines.

It is also important to note that the ranges at which the 180-dB levels (or greater) are achieved with the SURTASS LFA sonar are relatively independent of the local sound velocity profile, as they lie wholly within the region of near-field transition to spherical spreading losses. Under normal SURTASS LFA sonar operations, the loci of 180-dB levels will vary between a range of .75 to 1 km (.40 to .54 nm) of the source array and over a depth stratum of approximately +/- 35 m (115 ft) centered on the array. Due to practical source operational requirements, this range will for all practical purposes, always be less than 1 km (0.54 nm).

- Actual operating SL of the LFA transmit system (LTS) may be slightly (1 to 2 dB) less than that used in the RL calculations (theoretical maximum). No dynamic structure is ever operated at its absolute design limit for any significant period of time.
- Typical operational array shading may also reduce levels by a few dB. These signal-processing techniques are related to any active system, (e.g., radar), and result in reduction of unwanted signal strength through techniques such as side-lobe rejection.
- Use of signals away from the peak of the transmit band will also reduce levels by a few dB. The SURTASS LFA sonar band is not flat across the spectrum. The value used in the calculations above are based on the peak of the transmit spectrum. The full band is actually utilized in operations and reductions of 1 to 2 dB will again be realized.

By way of illustration, it is noted that a net reduction of 3 dB in SL by any combination of the above listed factors would reduce the 180-dB mitigation range to approximately 700 m (766 yds). It is important to note that the level predictions provided in Figures A-2 and A-3 are based on the maximum theoretical SL of the LTS source array.

c. <u>Mitigation Requirements of the HF/M3 System</u> - As shown in the performance calculations (Table A-1 below), the source level required for the HF/M3 system to effectively detect marine mammals (nominal target strength (TS) values for representative animals is shown in Table A-2) under the most adverse conditions (low TS and high noise) is on the order of 220 dB re 1µPa @1m.[8] The required operating frequency is in the range of that used by many odontocetes for echolocation. Figure A-4 illustrates the RL from the HF/M3 system out to a range of 10 km (5.4 nm). For the HF/M3 system itself, the 180-dB isopleth lies at a range of 100 m (328 ft) or less. Thus, it may be necessary to mitigate its level under certain circumstances.

Table A-1. Noise Limited Signal Excess (SE) Calculation.

Freq =	40 kHz	Wind Speed - Kts			
Rng =	1000m	5	10	20	30
	5	61	55	49	46
TS	-5	51	45	39	36
	-15	41	35	29	26
	-20	36	30	24	21
Freq =	40 kHz	Wind Speed - Kts			
Rng =	2000m	5	10	20	30
	5	34	28	22	19
TS	-5	24	18	12	9
	-15	14	8	2	-1
	-20	9	3	-3	-6
Freq =	40kHz	Wind Speed - Kts			
Rng =	3000m	5	10	20	30
	5	11	5	-1	-4
TS	-5	1	-5	-11	-14
	-15	-9	-15	-21	-24
	-20	-14	-20	-26	-29
DT = 12dB		SL=220dB			
Vertical BmWdth = 10 deg			AG=	21	
Horiz BmWdth = 8 deg			TD=	0.10	sec
SE = SL + PG - 2TL + TS - (NL-AG) - DT					

Freq =	30 kHz	Wind Speed - Kts			
Rng =	1000m	5	10	20	30
	5	65	59	53	50
TS	-5	55	49	43	40
	-15	45	39	33	30
	-20	40	34	28	25
Freq =	30 kHz	Wind Speed - Kts			
Rng =	2000m	5	10	20	30
	5	44	38	32	29
TS	-5	34	28	22	19
	-15	24	18	12	9
	-20	19	13	7	4
Freq =	30kHz	Wind Speed - Kts			
Rng =	3000m	5	10	20	30
	5	25	19	13	10
TS	-5	15	9	3	0
	-15	5	-1	-7	-10
	-20	0	-6	-12	-15
DT = 12dB		SL=220dB			
Vertical BmWdth = 10 deg			AG=	21	
Horiz BmWdth = 8 deg			TD=	0.1	sec
SE = SL + PG - 2TL + TS - (NL-AG) - DT					

Table A-2. Summary of Estimated Target Strengths of Various Marine Wildlife.

Broadside and Head-On Target Strength			
TS = 22.8 Log[L(m)] – 2.8 Log [1.5/f(kHz)] – 22.1[9]			
TS (Head-On) = TS (Side) – 6 dB [10]			
Length (L(m))	**TS (Side)**	**TS (Head-On)**	**Whale Type**
30	15	9	Blue/Fin
20	11	5	Humpback
10	4	-2	Calf, various
5	-3	-9	Pilot Whale
3	-8	-14	Beluga
2	-12	-18	Porpoise
1.5	-14	-20	Humans/E-Seal

[8] Many commercially available fish-finder, depth sounder and oceanographic sonar systems operate in this frequency range with source levels in the 220 to 230 dB re 1µPa @ 1m regime.

[9] Equation 2 from Au, W.W.L. 1996. "Acoustic Reflectivity of a Dolphin" J. Acoust. Soc. Am. 99(6): 3844-3848.

[10] Love, R.H. 1973. "Target Strength of Humpback Whales *Megaptera novaeangliae"* J. Acoust. Soc. Am. 54(5): 1312.

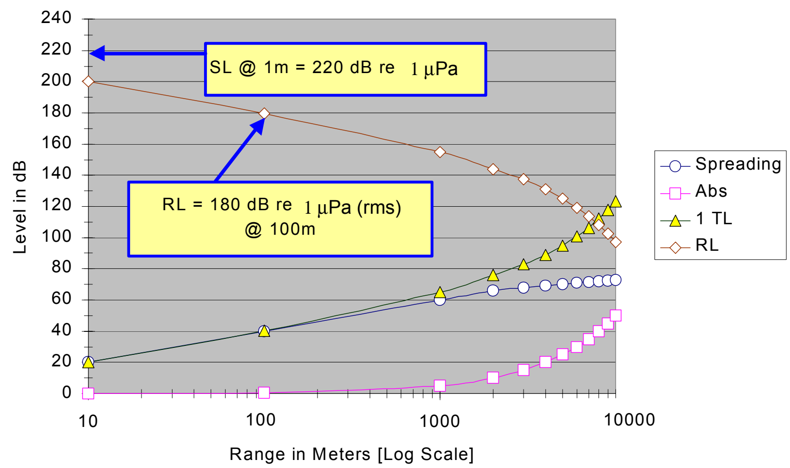


Figure A-4. HF/M3 System One-Way Transmission Loss to 10 km.

Two mitigation options for the HF/M3 sonar system are available: 1) limit the frequency to 30 kHz, and 2) if required, design the operating procedures so that the source level can be reduced as animals near the sonar. Thus, once an animal is detected approaching the SURTASS LFA sonar mitigation range, the LFA system can be shut down prior to its actual entry. As the animal is tracked in closer, the HF/M3 system will be adjusted to ensure that its own level does not exceed the nominal mitigation level of 180 dB; i.e., 100 m (328 ft) from the HF/M3 source.

d. <u>HF/M3 Design Approach</u> - There are no existing active high frequency (HF) systems that can currently meet the requirements for this application. An essential objective of the selected design was to have the system wholly PC-based using mainly commercial off-the-shelf (COTS) components and software throughout. This not only reduces procurement and support costs, but also allows rapid enhancement of system capability as more powerful COTS processing capability becomes available. These objectives, along with the low required scan rate and shallow depth requirement, led to the use of four mechanically-steered air-backed parabolic transducers. This dramatically reduced the number of channels (from approximately 60 down to 4), thereby simplifying system electronics and lowering cost.

From the LFA mitigation discussion above it was clear that the dominant feature of importance was the maximum detection range of the animal. This became the foremost design attribute of the system, as it had to exceed the LFA mitigation range under operational conditions. Because bearing accuracy was not as critical as range accuracy, eight-degree bearing sectors were more than adequate to detect the animal and roughly track its progress relative to the SURTASS LFA sonar platform. At ranges on the order of 2000 m (2200 yds) or less, the range and bearing rates on any detected animal would likely be quite high, and thus a relative track would be readily apparent. This attribute of the detection geometry also allowed for development of an automatic detection and tracking alert system. This natural track development goes a long way toward reducing the false alarm rate for an automatic detection capability. Once a mitigating detection has been made via the remote display at the

SURTASS Operations Center (SOC) Watch Supervisor Console (manned during all SURTASS/ LFA operations), the system will be manned until the event has ended with the animal leaving the zone.

It was desirable for a variety of reasons to keep the weight and size of all aspects of the system as low as possible. Using a modified mine/swimmer detection sonar would result in systems that were not designed originally for the LFA source configuration or PC-based processing. The operational configuration considered most effective from both detection and mechanical performance was to place the system integral to the source array, and at or near the top of the SURTASS LFA sonar VLA.

e. Dual-Use Potential - There is a significant dual-use opportunity for this system as a marine wildlife detection and tracking system, including detection of fish schools and a whale avoidance sonar. With such a lightweight and portable system, it is possible that it could be used in a roll-on/roll-off mode for transiting vessels. Other dual-use applications in the biological studies area abound.

2. Design Capabilities - The prototype of the fundamental system concept is shown in Figure A-5. In this photograph the system is installed in the towbody constructed for the engineering trials conducted in Baja Mexico in the Spring of 1999. The photograph shows the four-quadrant array of the source/receiver (S/R) components, each with its own parabolic lens. As described below, this quadrant arrangement is currently configured for the Research Vessel (R/V) *Cory Chouest* installation in a slip-ring arrangement, allowing continuous rotation of the S/R elements during scanning operations. Figure A-6 provides an illustration of the location of the HF/M3 sonar installed on the top of the SURTASS LFA sonar VLA system for the R/V *Cory Chouest* application.

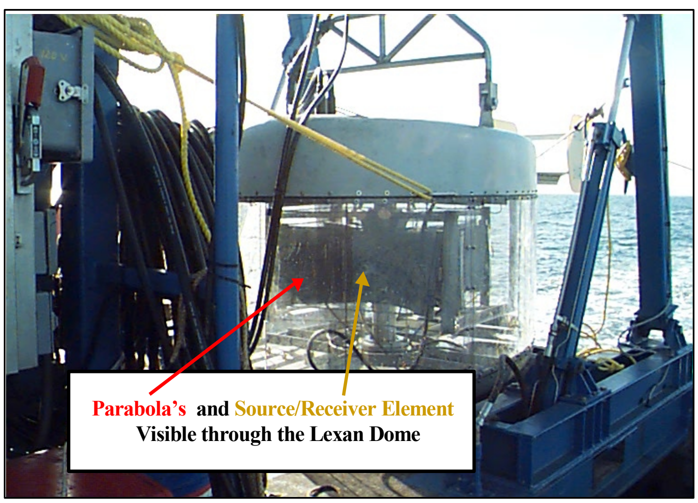


Figure A-5. HF/M3 Sonar Prototype.

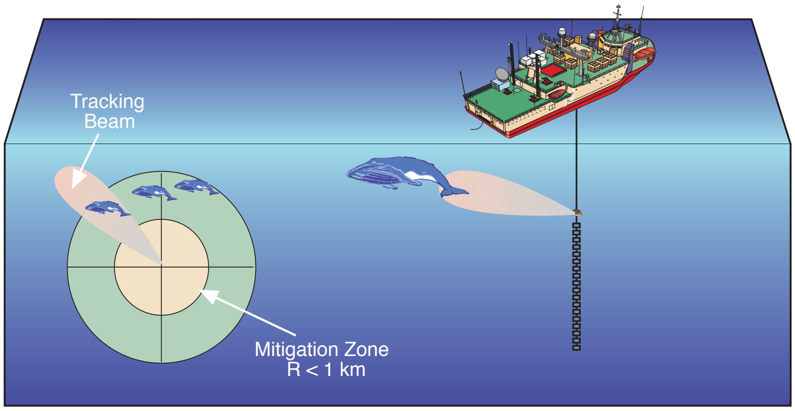


Figure A-6. HF/M3 Sonar Deployment Concept for R/V *Cory Chouest* Installation.

Figure A-7 shows a schematic representation of the system components that were physically installed at the top of the SURTASS LFA source array on R/V *Cory Chouest* in early 2000. The sonar system component assembly consists of an instrumented head, which contains four transducers (sources/receivers); each located in a focusing baffle. Each transducer in the towbody has a steerable horizontal beam width of approximately 8 degrees @ 30 kHz, and a steerable vertical beamwidth of approximately 10 degrees. The source/receiver technology being used allows for operation throughout the 30-40 kHz band, although it is expected that the portion of the band nearest to 30 kHz will be most used in practice. This is due to the decreased levels of absorption losses at the lower end of the band, and resultant improvement in net signal excess.

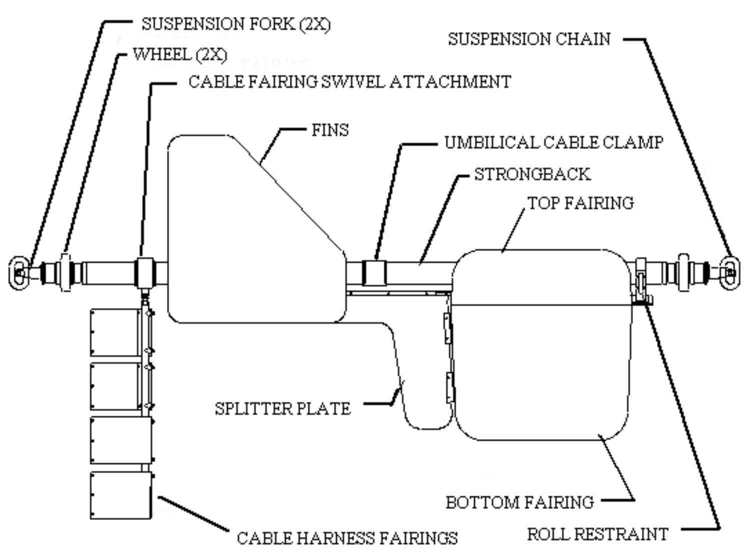


Figure A-7. Schematic of the HF/M3 Sonar Installed on R/V *Cory Chouest.*

The surface powering and processing package consists of a power amplifier, a signal conditioning box with anti-aliasing filters, and a PC outfitted with an analog to digital (A/D) board, digital signal processing (DSP) board, and relay board. Because the beams are fixed at the in-water array and no beamforming is required, processing and display can be performed on a fast PC. The display will plot the range of any target returns above set thresholds. Automatic detection will be based on both threshold and tracking parameters as discussed above. The display provided is a relative plan position indicator (PPI) polar configuration of the type that is usually associated with a variety of short-range detection systems. This configuration has been selected for this application as it shows all ranges and bearings in one format that is conceptually similar to a visual scan relative to the heading of the ship. It is identical to the format of a surface ship radar display, and one easily recognized by most personnel with any degree of sea-going experience.

a. Design Performance – The theoretical detection capability of this system is best described by the sonar term, signal excess (SE). The SE sonar equation is given by:

$$SE = SL + PG + TS - 2TL - (NL - AG) - DT \qquad (1)$$

Where,

- SE = Signal Excess. SE = 0 implies a 50 percent single ping detection probability.
- PG = Processing Gain [nominally 10 Log (T)], T = signal duration in sec.; e.g., T = 100 msec. This assumes a matched-filter or similar energy detector processor; i.e., SE is a Log ratio of the signal energy to noise spectra.
- TS = Target Strength of the animal being tracked. See examples in Table A-2.[11]
- 2TL = Two-way Transmission Loss. This is a sum of the losses due to spreading loss; e.g., 40 Log [Range(m)], and sea water absorption; e.g., 9.2 dB/km at 30 kHz, and 16.8 dB/km at 40 kHz. (One-way losses are half of those cited.)
- NL = Noise Spectrum Level in dB re 1μPa/$Hz^{1/2}$. At these frequencies this level is controlled by wind speed, V_W.[12]
- AG = Array Gain of the receiver, nominally 21 dB for an 8 degree by 10 degree focused-beam receiver.
- DT = Detection Threshold. This is the excess signal over a 0-dB signal-to-noise ratio (SNR) at which one expects a 50 percent single-ping unalerted detection to

[11] There are no definitive references on the TS of marine mammals, but the adventitious measurements that have been made seem to fit a broad-based relationship for the target strength of fishes (Urick, R.J. 1967. Principles of Underwater Sound for Engineers. McGraw-Hill Book Company. New York. [Sec. 9.12 et seq] and Dr. R. Love (pers comm. 1998)). These relationships imply levels ranging from +15 dB for large whales to –20 dB for humans and small odontocetes in the 30 to 40 kHz regime.

[12] Mine Warfare Environmental Pocket Handbook, PSI 1997, $NL= 40 + 10Log[V_W^2/(1+F(kHz)^{5/3})]$

occur. A nominal value of 12 dB has been used for the following calculations. Thus, a signal excess value of 0 dB corresponds to a SNR value of 12 dB.

As cited earlier, Table A-1 provides a design estimate of the system's capability at ranges from 1 to 3 km (0.54 to 1.62 nm) and at frequencies of 30 and 40 kHz. Note that the range of 3 km (1.62 nm) is 2 km (1.08 nm) beyond the greatest range at which the mitigation boundary of 180 dB for SURTASS LFA sonar can occur in almost all cases. The primary difference in performance between the two operating frequencies is the increased absorption losses at 40 kHz. The results in Table A-1 have been shown in a parametric format where range, TS, and NL have been varied over their full range of values. As can be seen, the system has excellent capability at 1 km (0.54 nm) for the smallest target, and the highest noise level. Under virtually all circumstances, any animal, especially the large whales, will be detected and tracked well before reaching the 1-km mitigation range.

It is important to note that the system is designed for noise-limited operations. This is fundamentally different than a hull-mounted whale collision avoidance system, which perforce must operate at the near-surface under reverberation-dominated conditions. In this near-surface type of sonar application, the acoustic noise floor is always controlled by the scattering of sound from the adjacent rough surface of the ocean. The resultant reverberation levels from this surface scattering are considerably higher than ambient noise, and require significantly more sophisticated processing techniques to overcome. By installing the proposed system on the SURTASS LFA source array (and therefore operating at depth), and using a narrow (order of 10 degree) and steerable vertical beam, the HF/M3 system can be tuned to minimize such surface interactions by adjusting the reverberation-controlled range[13] beyond the mitigation boundary.

b. <u>Processing Approach</u> – In developing the original performance objectives for the HF/M3 system, it was determined that the primary detection goal would be marine life with TS values in the 30 to 40 kHz regime greater than –20 dB (see Table A-1). This implies that environmental clutter with similar or lower levels can be ignored in our search for animals of interest. One approach that accomplishes the above objective is described as follows. If the transmission loss (TL) is known between the source and the target, together with the absolute source level (SL) then we can write the absolute RL energy equation for a given size of target (TS):

$$RL = SL + 10\text{Log}(T_{WF}) + TS - 2TL^{14} \qquad (2)$$

Knowing:

- The minimum TS of interest is –20 dB, a given,
- $TL = 20\text{Log}[R(m)] + 5R(m)/1000$; last term is nominal for absorption at 30 kHz[15],

[13] The nominal slant range with a -0.5 degree steer angle to the surface, and a 10 degree vertical beam is 2 km (1.08 nm). Greater steer depression would move this incipient reverberation range farther out. By having the source steerable, the in situ observed reverberation can be used to set the angle. This in situ tuning process will ensure noise-limited operations.

[14] This is the broadband energy form of the sonar equation; i.e., RL is the energy output of a matched-filter processor, Signal Energy.

[15] Schulkin, M., and H.W. Marsh. 1962. "Sound Absorption in Sea Water" J. Ac. Soc. Am. 34(7): 864-865. 5 dB/km one-way absorption is nominal for most temperate zones. Winter conditions in Northern Latitudes will increase to 6.5 dB/km.

- SL = 220 dB re 1μPa @ 1 m, nominal value, and
- The waveform (WF) is on the order of 100 msec in duration (T_{WF}) and 3000 Hz in bandwidth.

Then, the minimum absolute RL required as a function of range R(m) is:

$$RL_{MIN} = 220 + 10Log(T_{WF}) – 20 – 40Log[R(m)] –.01R(m) \quad (2a)$$
$$= 200 – 40Log[R(m)] - .01R(m), \text{ assumes } T_{WF} = 100 \text{ msec} \quad (2b)$$

Using a 30-kHz signal, the results of equation (2) are tabulated in Table A-3 for various ranges from 250 to 2500 m (820 to 8202 ft) for a 20 knot wind speed, and a 12 dB detection threshold.

Note that as TL increases (i.e., on the fringes of the beam or at regions where there is intense refraction) these SE values will decrease rapidly. Thus, beam steering must be judicious to ensure that the energy is put on the target within the primary mitigation zone.

Figure A-8 provides a TL plot generated by the TL model installed in the HF/M3 Onboard Integrated Display System. The result shown in this figure is representative of a typical temperate water application of the HF/M3 system deployed at a nominal depth of 110 m (360 ft). The figure is annotated to highlight the main features of the HF 10 degree transmit beam. The sidelobe beams are used in the TL calculation process, primarily to show the effect of potential surface reverberation at close ranges.

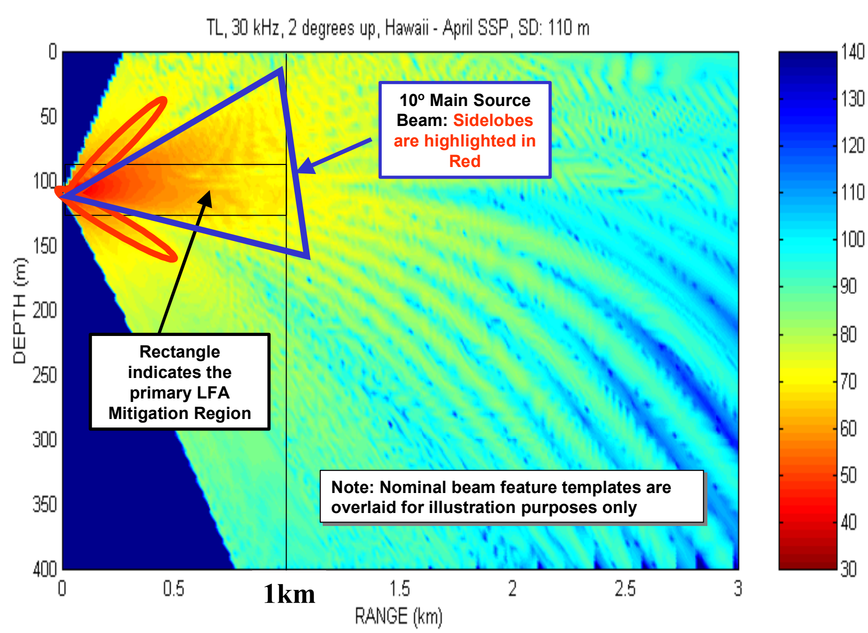


Figure A-8. HF/M3 Onboard Integrated Propagation Display System.

Table A-3. Spreadsheet Analysis for Equation (2).

Variables:								
DT	12	Detection Threshold						
Wnd	20	Windspeed in Kts						
Freq	30	Source Freq in KHz						
NL	41	Calculated Noise Spectra =40 + 10Log[Wnd^2/(1+Freq^{5/3})]						x
Agn	21	Array Gain of the System Receiver (10deg by 8 deg)						
TD	0.1	Signal Duration in sec						
TS	-20	Target Strength						
Relations:								
SNR = RL - (NL - AGN)								
SE = SNR - DT								
R(m)	Abs RL	SNR	SE					
250	92	71	59					
500	77	57	45					
750	67	47	35					
1000	60	40	28	<- Design Point				
1250	54	33	21					
1500	48	28	16					
1750	43	22	10					
2000	38	18	6					
2250	33	13	1					
2500	29	9	-3					
(shaded)	=> Calculated Value based on Windspeed & Frequency							

B. TEST AND EVALUATION

1. Preliminary Design Testing – Testing of system components and test tools such as artificial targets commenced in the Fall of 1998. The first component built was a single element of the proposed sonar array. The purpose of this testing was to confirm the following attributes of the system design: 1) Ability to attain theoretical source and receiver gain, 2) Operations at design depth with no degradation in component capability, and 3) Demonstration of system Figure of Merit (FOM) in a full-scale acoustic environment.

a. Testing at NUWC Facility, Seneca Lake, NY – As of mid-November 1998, the HF/M3 sonar design had successfully progressed through several critical stages from concept formulation to in-water testing of a single source/receiver (S/R) unit at the Naval Undersea Warfare Center (NUWC) Test Facility at Seneca Lake, NY. These results have been reported separately[16], and are summarized below.

The critical design element of the HF/M3 sonar was the highly directive S/R unit. This unit successfully passed all test objectives at the October 1998 test at Seneca Lake, demonstrating the following five essential operational parameters:

i. Operational Depth Capability - The S/R focusing capability was achieved with a parabolic reflector acting as a pressure release surface. The required low-impedance boundary was achieved with a Corprene™ layer epoxied to a glass reinforced plastic (GRP) backing structure. This material is depth-sensitive, but was designed to operate effectively to the specified design depth. Initially the design depth was limited to 91.4 m (300 ft), it was later increased to 213 m (700 ft) when it was decided to deploy the unit on the top of the SURTASS LFA source array. During the October 1998 Seneca Lake test, the system was tested to 91.4 m (300 ft) with no discernible degradation.

ii. Unit Source Level – Levels of 220 dB re 1µPa at 1 m were achieved with the amplifier used on the test. It was estimated that operational SL's of 6 dB higher would be available with the operational amplifier. Nominal transmit beamwidths of 10 degree vertical and 5 degree horizontal were achieved with the source. The measured transmit patterns very closely matched the theoretical patterns predicted using numerical modeling.

iii. Unit Vertical Steering – Vertical (gear drive) steering to ± 10 degree was successfully demonstrated during the Seneca Lake test.

iv. Unit Receiver Gain – Nominal gain against omni-directional noise of approximately 23 dB was demonstrated during the test. The lake environment was very quiet at these frequencies, and high (SNR) signals were achieved throughout the region of direct propagation.

v. Observed Signal Excess – At the Seneca Lake test depth, there was a downward-refracting ray path. This created a shadow zone at approximately 1686 to 1829 m (1800-2000 yds) for the 0 degree elevation ray at the artificial target (TS estimated at –14 dB) tow depth of 46 to 61 m (150-200 ft). At greater ranges, the TL to the towed target diminished rapidly due to the refractive effects.

[16] Wm.T. Ellison, "Program Objectives and Schedule for a High Frequency Marine Mammal Mitigation (HF/M3) Sonar System," MAI Report 331-2, Prepared for Mr. J. Johnson (NSMRL), dated 7 Oct 1998.

This condition was not dissimilar to that experienced off Pt. Hueneme and in Baja, California. In these later tests the absolute design requirement was a detection range of 1 km (0.54 nm) for a target in the –15 to –20 dB TS range. In the Seneca Lake environment, refraction was the dominant limiting factor in detection.

b. Propagation Modeling - The acoustic propagation modeling for the HF/M3 system was performed with a ray code based on BELLHOP. BELLHOP is a propagation modeling scheme developed at Supreme Allied Commander, Atlantic (SACLANT), and is a well-established ray code that implements a robust and accurate Gaussian beam/finite element beam algorithm. The code has the capability of tracing rays and computing TL in a range-dependent environment, with extensions to account for the vertical beam pattern of a given transducer in the transmission loss computation. It was particularly suited to this application. A typical output display of TL vs. range is provided in Figure A-8.

c. Development and Test of Artificial Targets – Target strength measurements were performed on four corner-reflector targets. Each target was composed of three orthogonal discs, and each disc had a 1/16 inch steel plate surrounded on each side by ¼ inch of Corprene™. For buoyancy calculations, volume was computed as 3 x πR^2 x (1/16 inch + (2 x ¼ inch); although this slightly overstates the volume because of the overlap. The diameters of the targets are given in Table B-1.

Table B-1. Target Diameters.

TARGET #	DIAMETER (in)
1	32
2	18
3	10
4	6

The calculated projected area of the target was approximately 0.87 x $(D/2)^2$. However, this appoximation is accurate only when the specular ray is near the 45/45/45 attitude. When one of the angles is close to zero, only a small fraction of the sound bounces off all three surfaces and reflects back toward the source. Other rays bounce off only two surfaces and reflect in other directions.

Figure B-1 shows the simplified case for a two-dimensional corner (a special case for the three dimensional corner reflector). For the oblique orientation on the left, only those rays in the area A1 would reflect back to the source, while those in area A2 would strike only one of the surfaces and would reflect to the left of the source. For the orientation on the right, all incident waves would reflect back to the target, thus the full area, A3, would be the projected area.

The test was performed at a Lockheed/Sanders quarry in Milford, NH. The setup is shown in Figure B-2. A 4 inch sphere was used as a source. An EDO hydrophone located approximately 1.8-2.7 m (6-9 ft) away was used as the receiver. The source, receiver, and target were all hung at a 9.1 m (30 ft) depth. The distance (L) between the receiver and target was chosen to guarantee that the target was not in the nearfield.

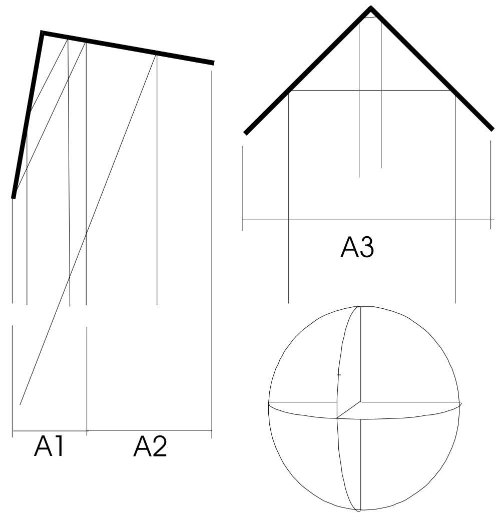


Figure B-1. Corner Reflector Projected Areas.

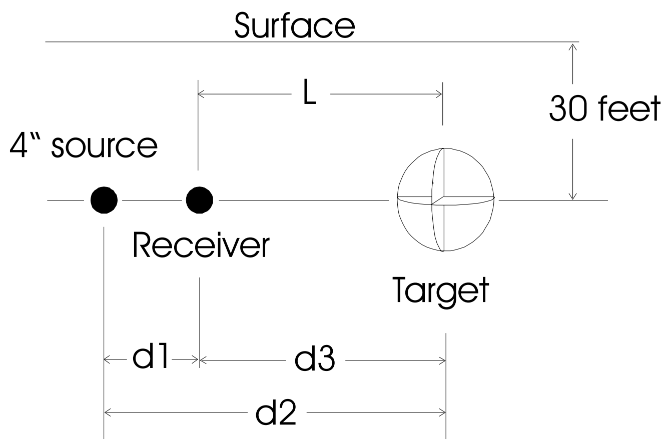


Figure B-2. Quarry Setup.

The source emitted short pulses at 30 and 40 kHz, and the signal received at the hydrophone was displayed on an HP3562 Spectrum Analyzer, after an appropriate delay to eliminate all reflections not associated with the target. A typical signal is displayed in Figure B-3. The direct path from source to receiver is shown in the upper part of the figure, and the target echo is the initial signal at 10.5 msec in the lower part of the figure.

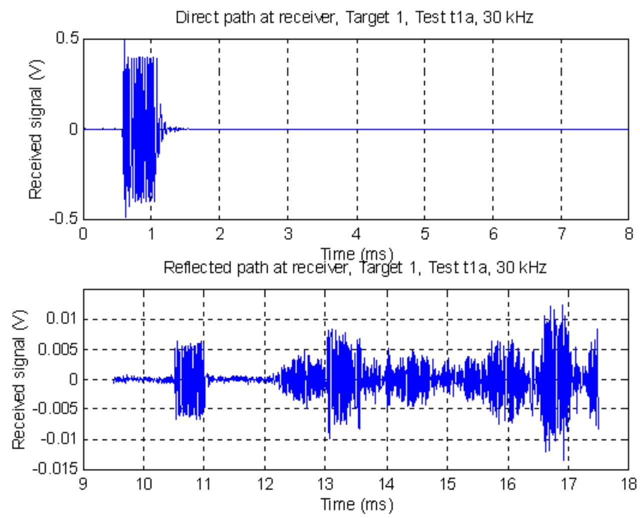


Figure B-3. Typical Signals, Direct Path and Reflected Path

The target strength can be measured using either the peak output or some weighted average. The target strength for the setup here is given by equation (3).

$$TS = -20\log(V_d)-20\log(r_1) + 20\log(r_2) + 20\log(r_3) + 20\log(V_r); \qquad (3)$$

Where r_1 = source to receiver distance

r_2 = source to target distance

r_3 = target to receiver distance

V_d = voltage at receiver from direct path

V_r = voltage at receiver from reflected path

During the data collection, the reflected path voltage was given a 30-dB gain because of the low values. This has been corrected for in the above equation. Table B-2 summarizes the data. RMS values are used.

Table B-2. Summary of Data.

Target ID	Number of pings, 30 kHz	Range of TS, 30 kHz	Median TS, 30 kHz	Number of pings, 40 kHz	Range of TS, 40 kHz	Median TS, 40 kHz
1 (32 inch diam)	13	-5 to 7	-2.1	10	-3 to 3	1.4
2 (18 inch diam)	6	-11 to –4	-7.4	7	-22 to -8	-9.1
3 (10 inch diam)	5	-24 to –10	-12.1	2	-22 to –18	---
4 (6 inch diam)	4	-25 to –20	-22.1	2	-26 to –21	---
2, on-axis	11	-3.7 to –3.4	-3.6	10	-16 to –2	-6.4
2, 45/45 orientation	11	-17 to –7	-10.6	10	-14 to –9	-9.9

2. Engineering Trial - The engineering trial of the HF/M3 sonar was conducted off the coast of Baja California, (Gulf of California) during March and April of 1999.[17] The results of this testing have been reported in a Quick-Look report.[18] Key results from that testing period are summarized below.

a. Overall Test Objectives – The test objectives were to: 1) Conduct engineering trials of the prototype system, 2) Detect and track man-made targets at target strengths, ranges and depths consistent with the proposed application of the system, and 3) Detect and track whales as encountered during the test.

b. Test Program –Table B-3 below provides a summary of the results of the overall testing prior to and through the Baja engineering trials.

Table B-3. Overall Test Objectives (Through Baja).

Component:	Test	Results/Comments
Functionability testing incl.: • Power Supply • Amplifier (L2) • Cabling (Single Unit) • SL Measurement • Receiver Gain • Noise Floor Measurement	Seneca Lake 10/98	Successfully completed initial engineering trials at Seneca Lake with a single source/receiver (S/R) element (final design is four). Both source and receive functions use the same transducer and focused beam housing (with a pressure release Corprene™ backing). These were tested at 61 m (200 ft) depths with minimal observed effects on beam patterns. An L-2 Amplifier was used in the test with measured source levels of 220 dB re 1µPa @ 1 m. Beam patterns were essentially identical with those predicted theoretically. Vertical steering of the S/R was also tested successfully.
Figure of Merit analysis, incl.: • PC-based signal processing • Broadband Waveforms • Tracking of –14 dB Target • Evaluation of Clutter levels	Seneca Lake 10/98	Demonstrated PC-based signal generation, reception of target, and processing of the return. All processes were calibrated to absolute levels. A –14 dB target was tracked at ranges to 1,646 m (1,800 yd). The S/R was at a depth of 61 m (200 ft) and the target varied between 30 and 61 m (100 and 200 ft). Signal characteristics tested included: Source Frequency - 30 and 40 kHz Bandwidth - 300 and 3000 Hz Duration – 10 and 100 msec

[17] W.T. Ellison, "Engineering Trials for the HF Prototype System," MAI 331-2 March 1, 1999.
[18] W.T. Ellison & P. Stein, "Quick Look Presentation: HF Sonar Engineering Trials Off Baja California: 27 March to 8 April 1999," MAI 331-2, April 22, 1999.

Table B-3. Overall Test Objectives (Through Baja) (cont).

Component:	Test	Results/Comments
Full System Checkout, incl.: • Salt Water Immersion • General Mechanical & Powering Continuity • Towbody Testing	NFESC Test period starting 3/99	Salt Water Immersion – Established correct ground for immersed systems. General Continuity – Required for all systems while immersed in salt water environment and while underway. Full power testing of the source elements was not conducted until the Baja Test. Towbody Testing - This test was the first in-water test of the interim towbody shape. Testing included: • Determination of dynamic towing properties as a function of cable scope, depth and tow speed. • Evaluation of nominal tow characteristics at 61 to 92 m (200 to 300 ft).
Full System Engineering Tests in Baja (La Paz, Mexico)	Baja La Paz 3/99	This test was a full-up system test in salt water, including: • System launch and recovery from Mexican host vessel. • Full evaluation of towing, winch ops, and tow control parameters. • Powering and Source Operation: Max SL=220 dB re 1µPa at 1 m, beam-width 10 degree vertical, 5 degree azimuth. Pulse Repetition Rate of 3 to 4 sec, scanning four 90-degree sectors every 1.5 min. Typical signal was of 100-msec duration and 300-Hz bandwidth. Total source transmit band that was evaluated was from 30 to 40 kHz. • Final Assessment of Systems – This covered all aspects of the HF/M3 sonar system and all supporting equipment, and was accomplished prior to departing La Paz for transit to Laretta field operations (includes all requirements for communications, navigation and powering).
Full System Engineering Tests in Baja (Laretta, Mexico)	Baja Laretta 3/99	First saltwater test of the system's full capability in detecting an underwater target, including: • Overall Objective - FOM at-sea evaluation over the full 30 to 40 kHz range with targets of –20, -10, and 0 dB TS. • Key Variables – HF/M3 tow depth, target depth, range to target. • Processing Objectives – waveform types, clutter reduction, clutter suppression techniques (thresholding).
Full System Field Demonstration Tests in Baja (Laretta, Mexico)	Baja Calif. 4/99	Follow-on to the above Engineering Test; demonstrated the system's capability to detect blue/fin whales (and other incidental marine life) in the Gulf of California, including: • Full evaluation of towing, winch operations, and tow control parameters. • Powering and source operation. • FOM at-sea evaluation over the full 30 to 40 kHz range with targets of –20, -10, and 0 dB TS.

c. Detailed Engineering Trial (Pt. Hueneme) Objectives – The engineering trials that commenced on 8 March 1999 at the Naval Facilities Engineering Service Center (NFESC), Point Hueneme, California, were the first seawater immersion test. More complex engineering trials were deferred to the Baja Mexico sea trials, which followed later that month. The key objectives of the Spring 1999 testing are listed and discussed below:

i. Salt Water Immersion, System Continuity Checks – This was the first full immersion test in salt water for the system and was important to evaluate grounding strategies. The system could not be operated at full power at Port Hueneme; thus full-scale FOM testing was precluded. However, low-level system powering was conducted to evaluate general continuity in full tow configuration.

ii. Tow Configuration – At this point in the development, the towbody, sonar configuration and assembly, and desired tow characteristics were near final design. Although final strength member (combined tow/power/signal) tow cable was still in design/construction, this did not affect the overall conduct of these trials, beyond adding time to marry-up or disconnect the cabling components on launch and recovery. The towbody testing was completed at NFESC just prior to the Baja Engineering Trials (below), allowing for good carry-over of the learning curve from that test in both location, personnel, tow vessel and equipment. Of critical importance at this stage was the ability to deploy to a specific depth (61 to 76 m (200 to 250 ft))[19], and to tow in a near horizontal (±2 to 3 degree) configuration at a nominal tow speed of 2 to 4 kts (3.7 to 7.4 kph).

d. Detailed Engineering Trial (Baja) Objectives – The engineering trials were conducted during the two week period commencing 29 March 1999 at La Paz, Mexico, and continued offshore of Laretta, Mexico. These were the first full-up tests of the operational sonar system and the test towbody combined. It was also the first-full power seawater test. This test period was critically important for two reasons: 1) Evaluating the effect of seawater absorption on signal excess, and 2) Evaluating the scattering effects of actual ocean biologics on the sonar system's performance. The primary objectives of this test were related to sonar performance (Figure of Merit (FOM), False Alarm Rate (FAR), Classification and Tracking, and environmental acoustics (EVA) assessment and modeling). These key test objectives are discussed below.

i. Figure of Merit (FOM) – Establishing the FOM of the system in the field was critical to future operational success. The initial checkout of the system was accomplished using procedures and equipment identical to that used in the Seneca Lake test in October 1998. These preliminary calibration tests established calibrated on-axis source levels and receiver gain, as well as all of the associated factors related to powering, filtering, gain settings, etc. It was not necessary to fully duplicate the transmit and receive beam patterns, due to the precise nature of the work performed at Seneca Lake on the first S/R unit. These tests were conducted with the towbody within its operational configuration, and in association with a second target platform that contained the calibration source and receiver systems.

[19] The layer depth in Baja was estimated to be around the 61 m (200 ft) depth during the test period. The HF/M3 sonar needed to be somewhat below this, thus the 61 to 76 m (200 to 250 ft) requirement. The final design is capable of depths to 213 m (700 ft).

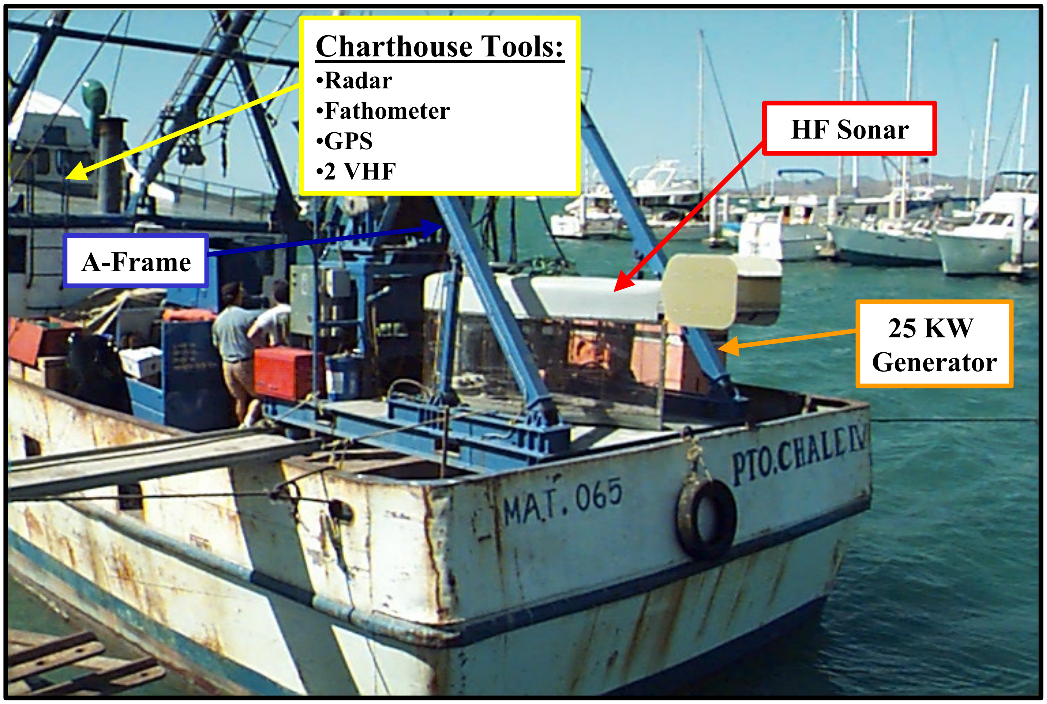


Figure B-4. HF/M3 Test Vessel Showing A-Frame and HF System Fairing Body.

The FOM, SE, RL and SNR equations are written below, with each of the several terms subsequently discussed as to its role in the proposed testing:

$$\text{FOM} = \text{SL} + \text{PG} + \text{TS} - (\text{NL-AG}) - \text{DT}$$
$$\text{SE} = \text{FOM} - 2\text{TL}$$
$$\text{RL(1 way)} = \text{SL} - \text{TL (Abs value)}$$
$$\text{RL(2 way)} = \text{SL} + \text{TS} - 2\text{TL (Abs value)}$$
$$\text{SNR} = \text{SE} + \text{DT}$$

Figure B-4 provides a general view of the proposed testing arrangement for the engineering trials, together with the principal sensors required.

ii. <u>Test Measurements</u> – The following test measurements were made:

- SL_1 – Source level to be measured as $SL_1 = RL_2 - TL_{12}$, where RL_2 was the absolute level measured on a calibrated receiver and TL_{12} is the transmission loss. At the outset, the test geometry was set up such that TL_{12} was described by spherical spreading [20Log(R)]. This established SL_1 to an absolute level. The subsequent testing of the [calibrated] source with the [calibrated] receiver could then establish highly accurate TL_{12} plots as a function of range and the respective source and receiver depths.

- NL – Noise Level, or the omni-directional ambient noise level was measured at the calibrated R_2 receiver, during a period when the sources were not operating and the receiver platform was still in the water, engines off (if possible). This was a continuing requirement through the trial.
- PG – Processing Gain was a function of the waveform (WF) being used, nominally 10 Log(T), where T = WF duration in seconds.
- AG – The measured Array Gain from the Seneca Lake testing was used.
- NL_{BM} – This was a shorthand notation for $(NL - AG)_1$, which was the actual level measured on the HF receiver. Thus, with ongoing measurements of NL_2 and NL_{BM}, and knowing the value of AG_1, NL_{BM} vs. $NL_2 - AG_1$ was compared and evaluated.
- TS – Target Strength values of the targets suspended from vessel #2 (RHIB) were pre-calibrated after construction. There were three targets with nominal values of –20, –10, and 0 dB re 1 m^2. These were deployed at various depths and ranges from the HF/M3 system to evaluate system capability.
- DT – Detection Thresholds were determined through the testing process. In situ determination of this value was found from the observation of the lowest SNR that was reliably detected 50 percent of the time. A starting value was gleaned from the Seneca Lake data set. It was a function of the WF type used; however, an engineering estimate of this value was determined based on the results from this test.

iii. <u>False Alarm Rate (FAR)</u> – In the absence of other processing techniques, the false alarm rate was a strong function of target SNR and thresholding. Within the design parameters of the system defined by the maximum (high probability of detection (PD)) detection range[20] of 1 km (0.54 nm) and the lowest TS expected (-20 dB), the FAR would be explored during the test by examining all returns above SNR=0 on a statistical basis vs. the target SNR as a function of range and TS. Typically this would be accomplished by radial runs toward the target starting from ranges on the order of 3658 m (4000 yds) and finishing at the system blanking range (order of 91 m (100 yd)). Both WF selection and thresholding were expected to play a major role in establishing FAR mitigation techniques. WF selection at this juncture of the design was in the form of variations on signal duration and bandwidth. Preliminary results from the Seneca Lake test provided guidelines for the appropriate WF to test during the engineering trials.

iii. <u>Classification and Tracking</u> – Classification and tracking was evaluated concurrently with FAR. In addition to radial runs, there were closest point of approach (CPA) runs with varying CPA out to 1 km (0.54 nm). It was important to establish the ability of the system to detect, track and classify targets at ranges beyond the high PD range in order to establish a warning interval before an animal approached the SURTASS LFA sonar mitigation zone (180-dB sound field).

iv. <u>EVA Assessment and Modeling</u> – EVA requirements, separate from ambient noise, were centered primarily on the layer depth and ray path estimations for the HF transmitted signal. This,

[20] In addition to range this was also delimited by the main beam of the SURTASS LFA sonar system. This region of high PD was approximated by a cylinder centered on the geometric center of the SURTASS LFA source array with a radius of 1 km (0.54 nm) and height of 73 m (80 yds).

in turn, drove the setting of the vertical steering angle on the HF system and the optimal refracted path for detection within the high PD zone.

e. Trial Plan in Baja – Table B-4 below provides the Baja schedule for achieving the listed objectives. Many of the activities had considerable overlap in their objectives and were conducted simultaneously.

f. Detailed Engineering Trial Support Requirements – In addition to the HF/M3 system installed in the towbody, the following platforms and support were used:

- Tow Ship – The motor vessel (M/V) *Pto. Chale* was the primary engineering center during the test. All testing was conducted during daylight hours. In addition to the requirements for the HF/M3 system, the ship provided the following:
  - Navigation (GPS) and communications support (LOS UHF/VHF) - The GPS output was in a form that could be downloaded and plotted for reconstruction in MATLAB or similar routines.
  - EVA Support - A portable sound velocity profile (SVP) capability and EVA ray trace model were available throughout the test period.
  - Fathometer - The shipboard fathometer was used throughout the test for water depth measurements.
- Support Platform (RHIB) – During the Baja test this platform performed target deployment duties and communicated with the tow ship via VHF.

g. Test Results - The HF/M3 sonar system trials were conducted out of the port of La Paz in Baja, Mexico. The system was installed onboard a leased fishing vessel, M/V *Pto. Chale*, as shown in Figures B-4 through B-5. The nominal test configuration (Figure B-6) required the use of a small craft to deploy calibrated targets as shown in Figure B-8. The small craft and its suspended target were positioned at a specific location and the M/V with the HF/M3 system deployed and maneuvered at specified ranges and bearings from the target. The basic geometry used during the testing is shown in Figure B-7. This testing was planned to determine the ability of the system to detect and track targets of the same size as whales expected to be found in the Baja region. The results of this testing are summarized along with additional detailed photographs of the vessels and installed equipment used on the test.[21]

[21] W.T. Ellison & P. Stein, "Quick Look Presentation: HF Sonar Engineering Trials Off Baja California: 27 March to 8 April 1999," MAI 331-2, April 22, 1999.

Table B-4. Baja Trial Plan.

Key Activities from start of Day # 1 Onboard Tow Vessel in La Paz													
Events:	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Dockside Setup & Arrival	X												
2. Tests Offshore LaPaz		X											
3. Underway Transit to Laretta, LV early AM, Arr Late Afternoon			X										
3. Onsite off Laretta: Buffer for Add'l Tow Testing and unforeseen problems				X	X								
4. System ChkOut, Comms, etc.				X	X								
5. Calibration, Noise Floor, EVA				X	X	X							
6. FOM Runs with variable steering WF, TS, CPA, & Tgt Depth as req'd					X	X	X	X	X	X	X		
7. Evaluation of DT, FAR, Classification issues & Tracking					X	X	X	X	X	X	X		
8. Demonstration of whale detection and tracking							X	X	X	X	X	X	
9. Transit to LaPaz													X

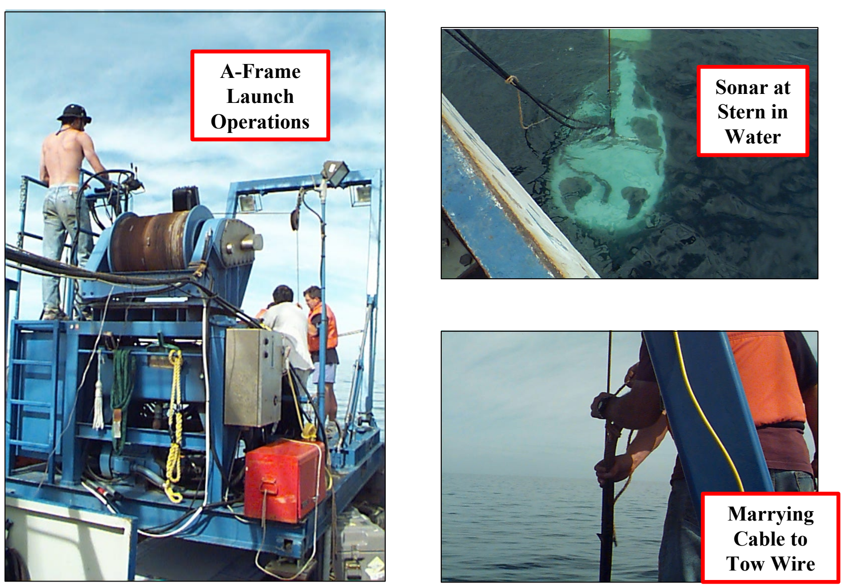


Figure B-5. A-Frame Launch Operations.

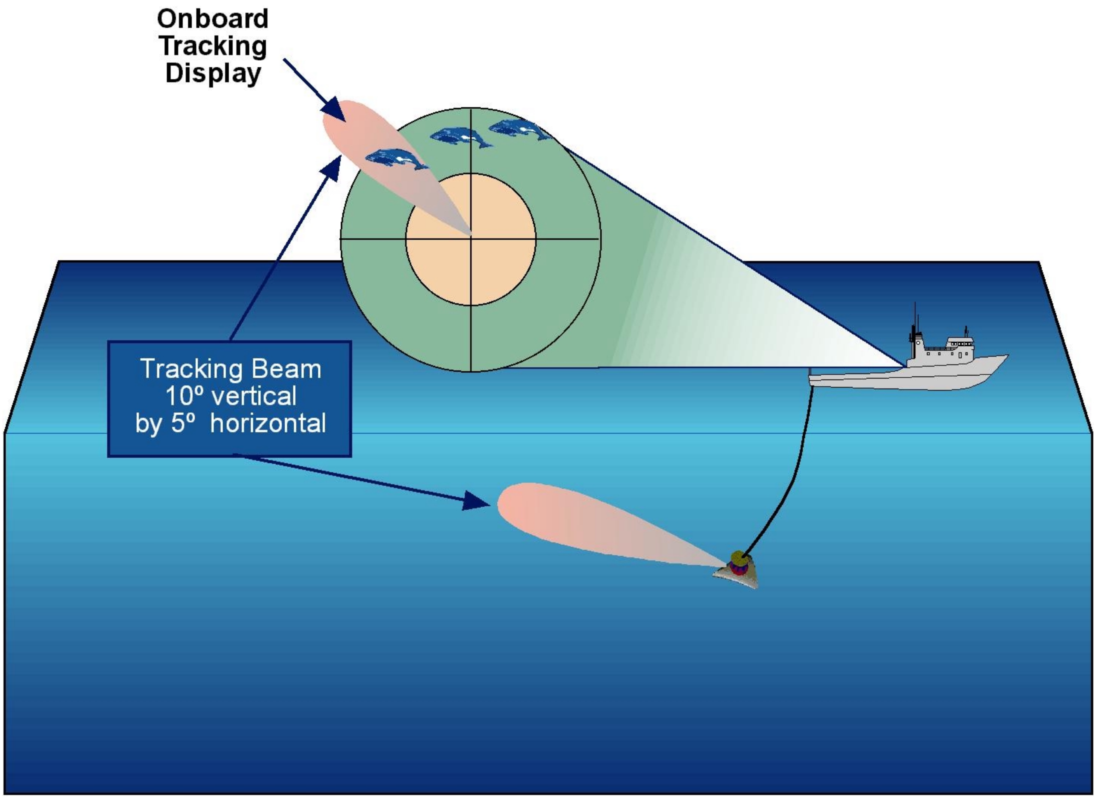


Figure B-6. HF/M3 Sonar Baja Test Configuration.

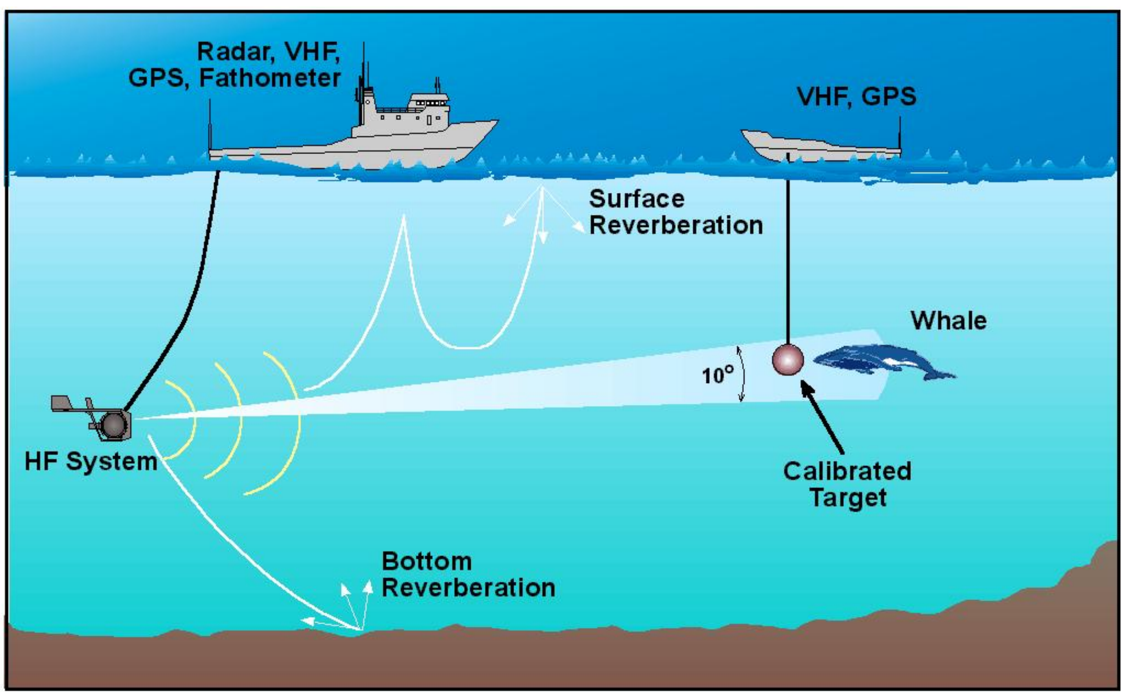


Figure B-7. Principal Test Elements for the Baja Trials.

Figure B-8. RHIB with the 32 inch Diameter Target (TS = -2.1 dB).

The bulk of the testing was conducted in a relatively shallow channel off of Isla Habana, 92.7 km (50 nm) north of La Paz (Figure B-9) where there were whale sightings. Most of these sightings of diving/feeding whales were in 61 to 91 m (200 to 300 ft) of water, between the vessel and the shore. This resulted in the sonar being aimed directly toward rapidly shoaling water with high bottom reverberation as an unwanted byproduct. The goal then was to attempt to detect whales in the deeper water along the axis of the channel, although such whales would not be expected to be diving to the depth desired (61 to 91 m (200 to 300 ft) on the axis of the sonar beam) as they would normally be transiting and not feeding.[22] Several transiting whales were successfully detected and tracked during this test period in the deeper parts of the channel.

Toward the end of the test period, operations were moved back toward La Paz to a deep water location, shown in Figure B-9. The results from this test period are summarized in Figures B-10 and B-11. These figures show a typical whale and target return from that location with a SNR of 30 dB or greater. Whale detections were actually made at ranges in excess of that for the large target (nominally twice the required SURTASS LFA sonar mitigation range). No whales were observed at any closer range. One large blue whale was actually sighted and detected at four different locations relative to the M/V-towed system, all at distances on the order of 2000 m (6562 ft). In one of these instances, this whale surfaced within 100 m (328 ft) of the support vessel (RHIB) towing the target. The most impressive result from this test sequence was the lack of clutter in the detection display. In this deeper water location the source beam was held fully within the water column with no interactions with the surface or bottom within the nominal mitigation range window. This was the situation expected to be found in most SURTASS LFA sonar operational environments.

[22] Pers. Comm. Dr. D. Croll, team leader conducting whale observations in the same location.

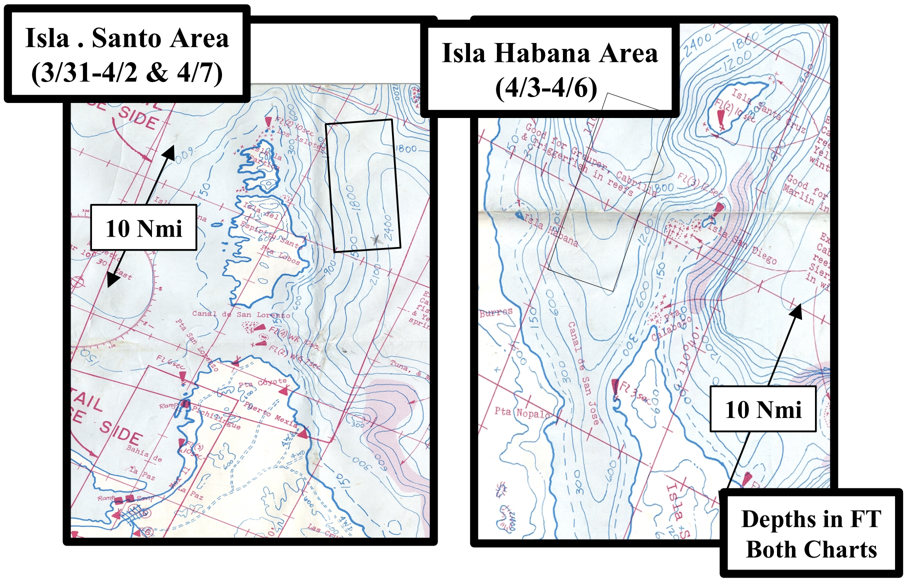


Figure B-9. Operating Areas for the HF/M3 System Testing in Baja.

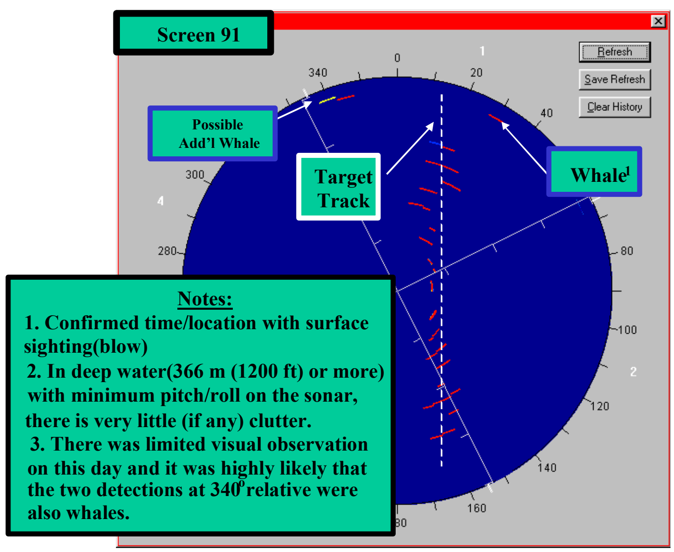


Figure B-10. Detection/Tracking Screen Showing Target (-2 dB) and Whale Detections.

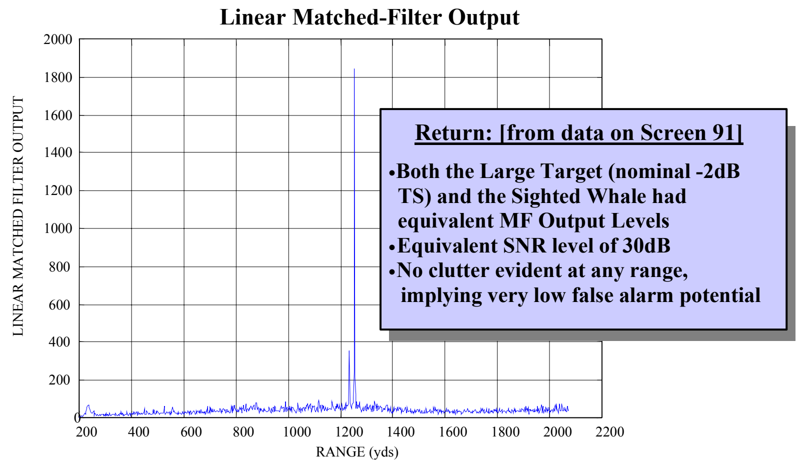


Figure B-11. Typical Target/Whale Return.

3. S/R Depth Tests - Following the Baja tests, it was decided to modify the planned installation of the HF/M3 unit by mounting it at the top of the SURTASS LFA sonar source array, instead of as a separate towbody. This resulted in increasing the operational depth requirement of the HF/M3 sonar to 213 m (700 ft). The CORPRENE air-backing used in the prototype transducers was inadequate at 213 m (700 ft). Thus, a development effort was initiated to find a suitable replacement reflector. This effort resulted in layered fiberglass construction of a single parabolic reflector for use in the redesigned HF/M3 sonar unit, which was tested at the NUWC Acoustic Pressure Tank Facility (APTF) on 6 October 1999. The reflector was constructed of a glass fiber/epoxy resin shell and a Coremat core, with an ITC 1032 transducer located at the focal point of the parabola. The purpose of the test was to quantify the transmit performance of the device at depth pressures up to 305 m (1,000 ft) (500 psi) depth.

a. Test Procedure - The desired data products from the test were the on-axis transmit voltage response (TVR) and the relative response vs. angle of the device (in transmit mode) in both the horizontal and vertical directions, measured at pressures that were representative of the expected operational depth range of the device.

The APTF layout is shown in Figure B-12. The tank has two ports, the larger of which has a 73 inch diameter opening. The transducer to be tested was mounted on an underwater mechanical rotator unit and placed in the large opening of the tank. A standard hydrophone (H52) is placed in the smaller port and used as a receiver at a distance of 4.7 meters (15.4 ft) from the source being tested. Measurements were made at pressures of 100, 200, 300, 400, and 500 psi.

The TVR for the bare ITC 1032 (without the parabolic reflector, Figure B-13) at frequencies between 30 and 40 kHz was first measured.

ACOUSTIC PRESSURE TANK FACILITY (APTF)

MEASUREMENT SYSTEM: VXI data acquisition system featuring 6 channels simultaneous sampling. CW, pulse, and arbitrary waveform generation. Computer-controlled acoustic measurement system provides active and passive acoustic measurements, directivity, echo reduction, insertion loss and electroacoustic characteristic measurements. Data report provided as printed and/or PC based formats (Stanford Graphics). Data can also provided on disk in ASCII format.

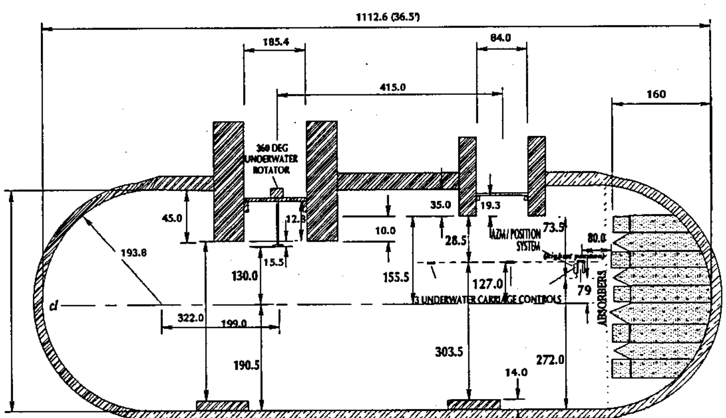


Figure 1
(ALL DIMENSIONS IN CENTIMETERS)

ACOUSTIC PRESSURE TANK

TANK SIZE:	Closed tank, 3.81 m diameter, 11.1 m long access port is 1.85 m in diameter. Tank is lined with Insulkrete sound-absorbing wedges; exterior thermally insulated.
MEDIUM:	Fresh Water
TOTAL WEIGHT FULL OF WATER:	1,054,504 Lbs
FREQUENCY RANGE:	1 to 350 kHz (typical)
PRESSURE RANGE:	0 to 2700 psig
MAXIMUM SIMULATION DEPTH:	6226 FT
TEMPERATURE RANGE:	2 to 45 degrees C (35 to 113 degrees F)
UNIT UNDER TEST WEIGHT:	6000 lbs maximum on rotator shaft 100 lbs maximum on carriages
MOUNTING SHAFT:	See figure 2

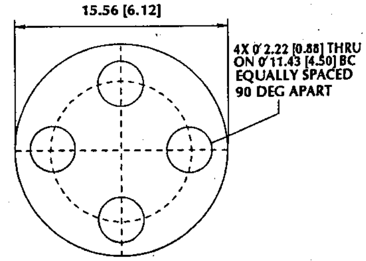


FIGURE 2 Rotator shaft attachment, Acoustic Pressure Tank Facility

Figure B-12. Schematic of the NUWC Acoustic Pressure Tank Facility.


Figure B-13. Bare ITC 1032 Transducer Rigged for Testing in the Acoustic Pressure Tank Facility.


Figure B-14. Parabolic Reflector with an ITC 1032 at the Focal Point, Mounted on the Mechanical Rotator Unit.

Next, the parabolic reflector was mounted to the rotator unit in a horizontal orientation using a custom fixture (Figure B-14). The fixture was designed to locate the center of the device on the centerline of the tank axis to maximize clear time between the direct path to the receiver and reflections from the walls of the tank. At each pressure, beam patterns were measured at 30 and 40 kHz, and then on-axis TVRs were measured between 30 and 40 kHz, in 250-Hz steps, using the APTF measurement system.

After measuring the horizontal beam pattern data, the device was re-rigged with the parabola rotated about its axis 90 degrees, so that the rotation was in a "vertical" direction relative to the orientation of the parabola in the HF/M3 unit.

b. Results - TVR data for the bare ITC 1032 transducer are shown in Figure B-15 for pressures of 100, 200, 300, 400, and 500 psi. The results show only minimal dependence on pressure, and are in good agreement with the manufacturer's specifications.

Nominal TVR data for the parabolic reflector device are shown in Figure B-16 for 100 psi. TVR data taken at 200, 300, and 400 psi are all in good agreement with data shown for 100 psi. Since the ITC 1032 is omni-directional and it was assumed that the side lobes of the parabolic reflector were very low, the bare hydrophone TVR data can be subtracted from these data to get an estimate of the Directivity Index (DI) of the device. Approximate DI vs. frequency computed using this method is shown in Figure B-17. Based on these data, using an average TVR value of 170 dB // 1 μPa at 1 meter and measured HF/M3 system amplifier output voltage of 50 dB re 1 V_{rms}, the expected maximum source level of the system can be computed to be 220 dB re 1 μPa at 1 meter over the frequency range of 30 to 40 kHz.

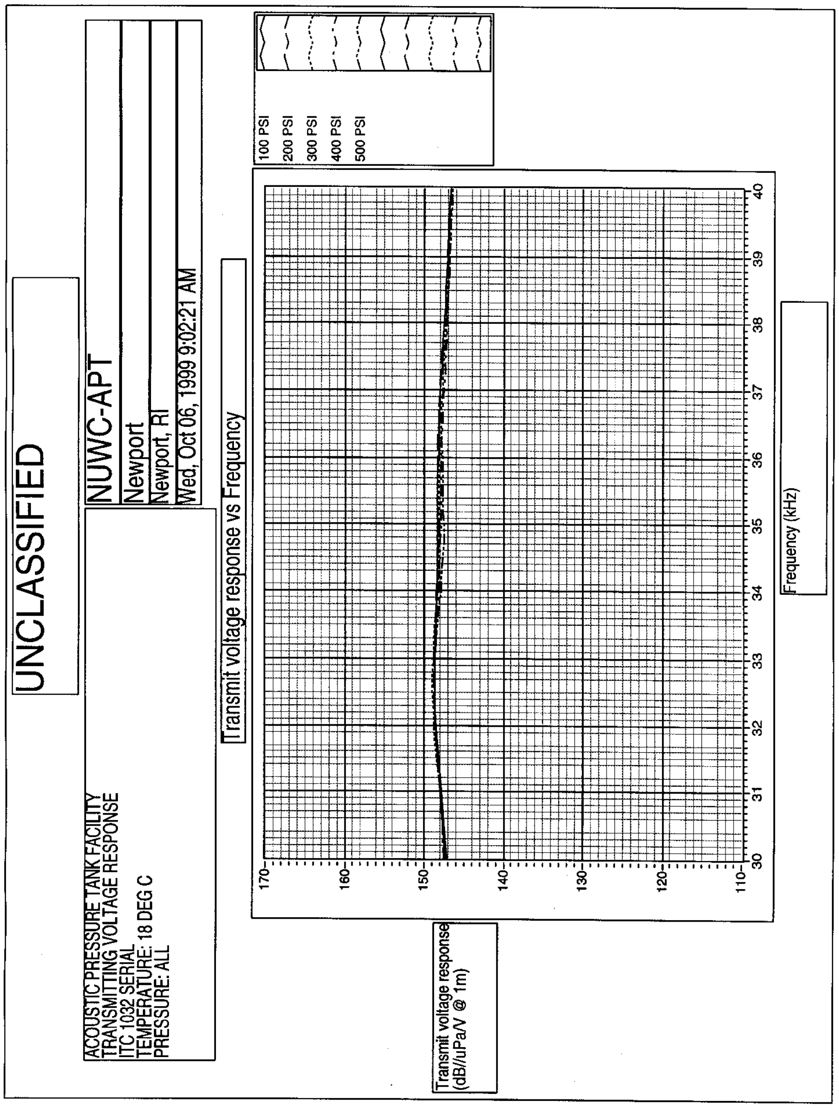


Figure B-15. Measured TVRs for Bare ITC 1032 at Pressures of 100, 200, 300, 400 and 500 psi from 30 to 40 kHz.

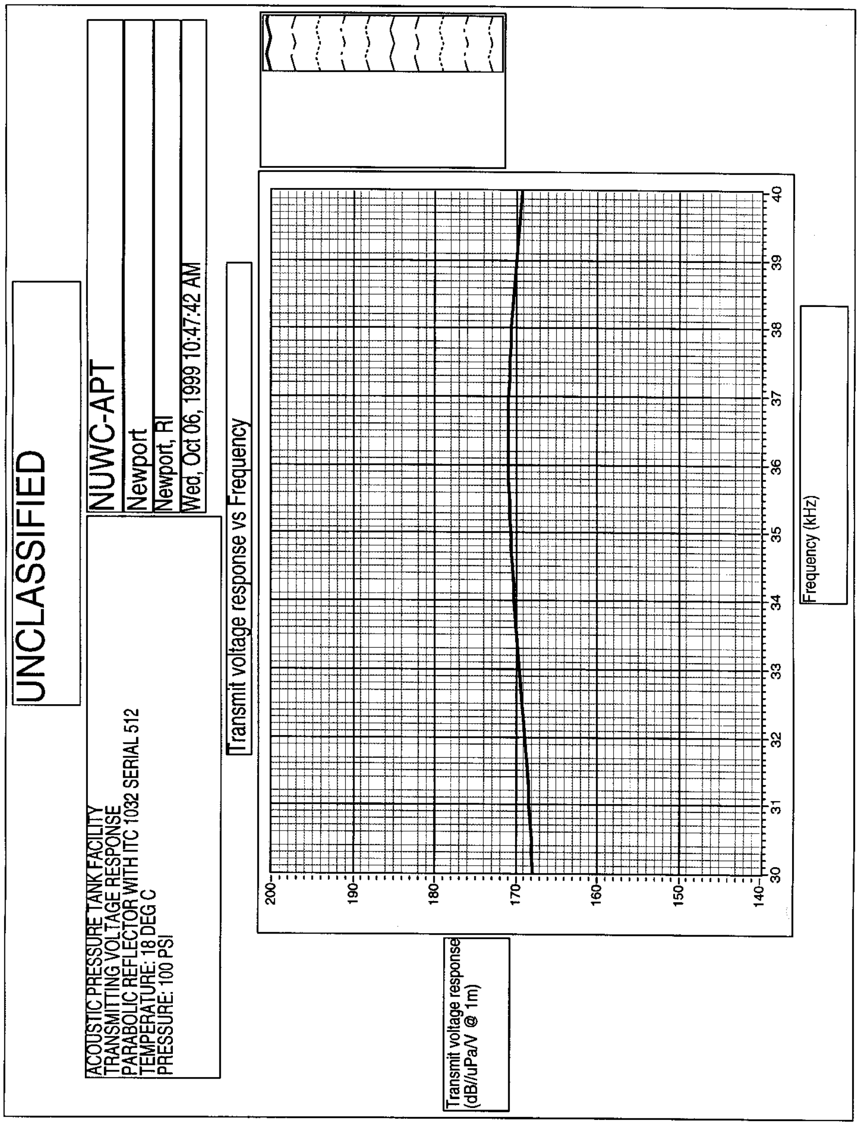


Figure B-16. Nominal On-axis TVR for Parabolic Reflector.

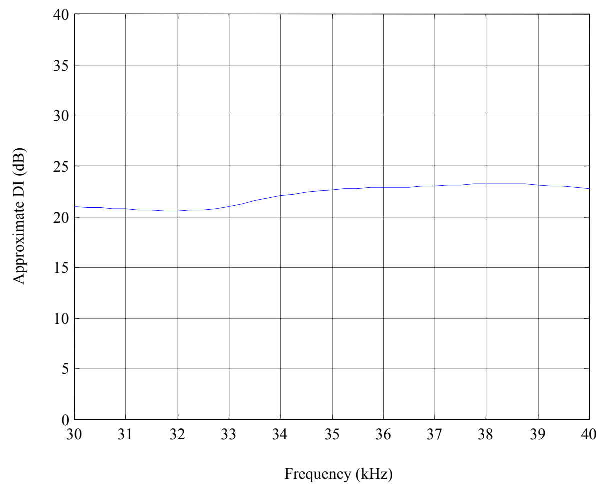


Figure B-17. Approximate Directivity Index (DI) of the Parabolic Reflector, Obtained by Subtracting the Nominal Bare Hydrophone Measured TVR from the Measured On-axis TVR of the Parabola.

At 500 psi (equivalent to roughly 305 m (1000 ft) depth), a sudden decrease in the TVR data was observed. It was later determined that the parabola structure had taken on water and lost its reflective properties at this pressure.

Beam pattern data at pressures of 100, 200, 300, and 400 psi were consistent with each other. Representative beam patterns at 30 and 40 kHz are shown in Figures B-18 and B-19. Based on these data, the 3 dB down beamwidth of the device was 7.9 degrees at 30 kHz and 5.0 degrees at 40 kHz. Because the device flooded at 500 psi, no subsequent beam pattern data (vertical patterns) could be measured.

c. <u>Conclusions</u> - The acoustic performance of the HF/M3 sonar parabolic transducer was as expected. The relevant measured acoustic parameters are summarized in Table B-5. Structurally, the device survived to an equivalent depth of 243 m (800 ft). At 305 m (1000 ft) (500 psi) the device took on water and lost its reflectivity. The failure was due to the collapse of a number of air voids on the edge of the reflector, which had formed during the manufacturing process. Since then, the manufacturing process has been refined to ensure adequate transducer construction. Further testing was conducted to insure an adequate margin of safety. However, for quality assurance, each parabolic transducer constructed for the HF/M3 sonar will be pressure tested.

Table B-5. Measured Acoustic Parameters for the Parabolic Reflector Device.

	Bare Hydrophone TVR (dB // µPa/V @ 1m)	**TVR with Parabolic Reflector (dB // µPa/V @ 1m)**	**Expected Max SL w/ HF/M3 amp (dB // µPa @ 1m)**	**DI (dB)**	**Beamwidth (3 dB down, degrees)**
30 kHz	147.0	168.0	219	21	7.9
35 kHz	148.0	171.0	222	23	---
40 kHz	146.5	169.0	220	22	5.0

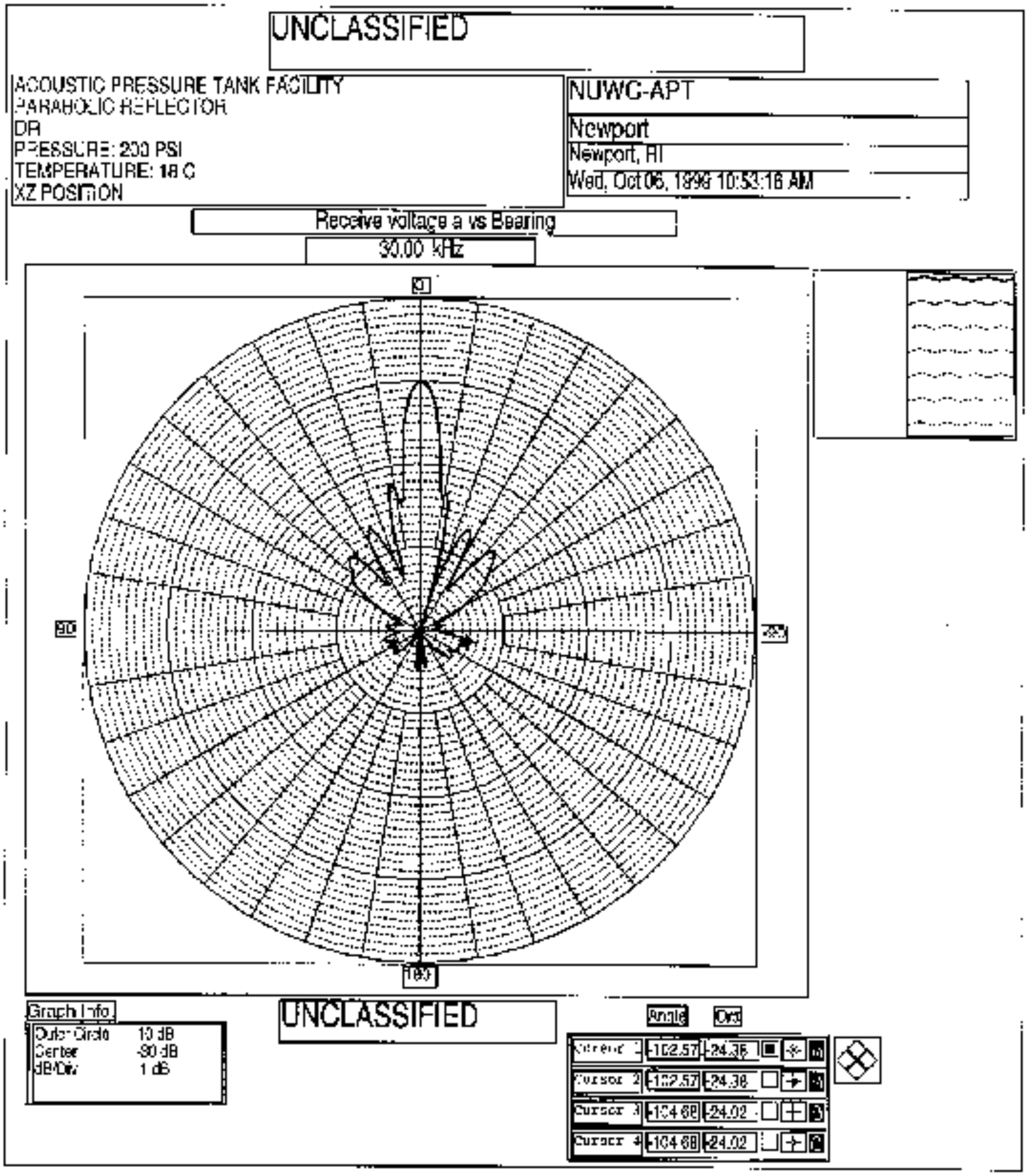


Figure B-18. Nominal Measured Transmit Beam Pattern for Parabolic Reflector at 30 kHz.

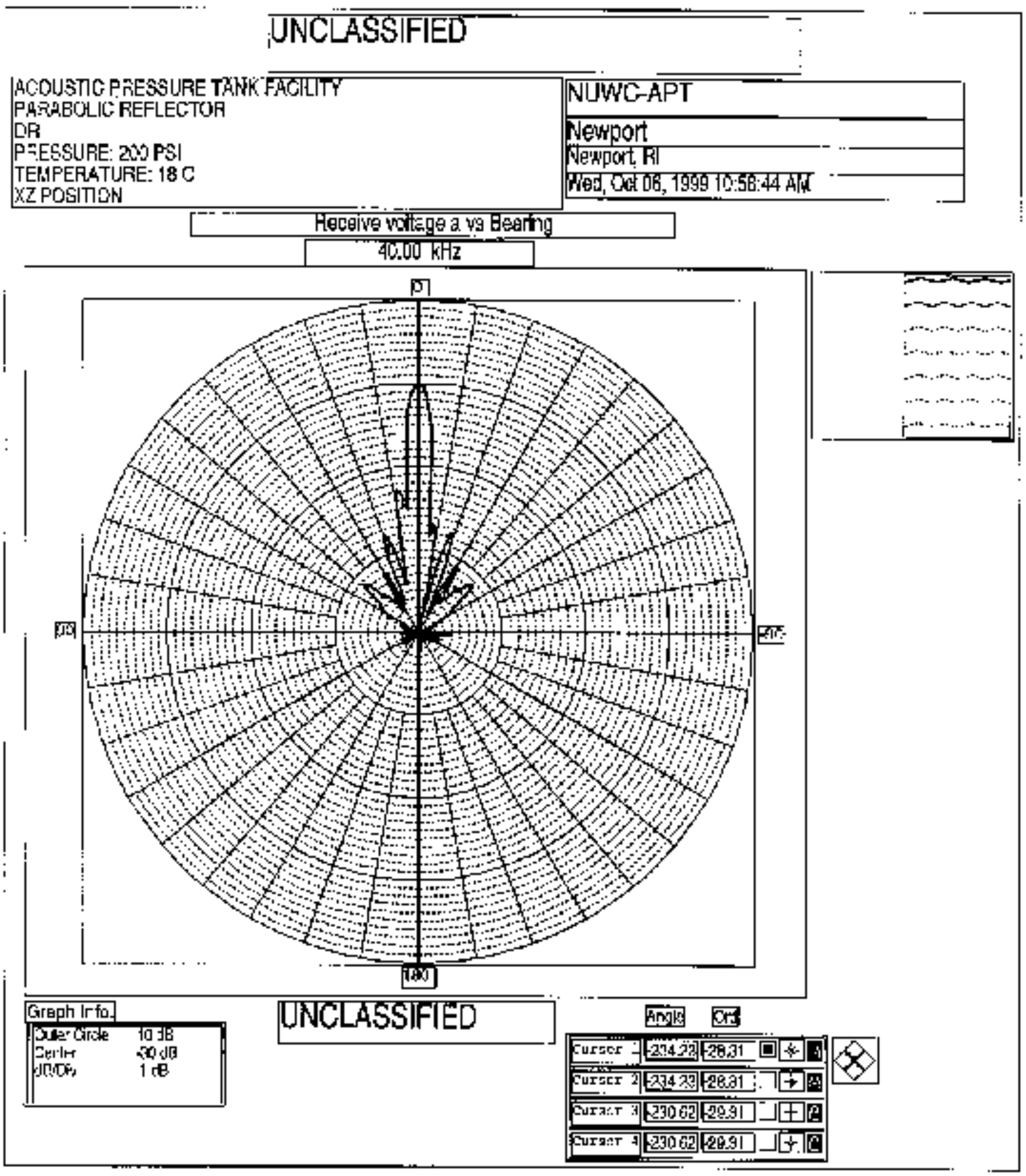


Figure B-19. Nominal Measured Transmit Beam Pattern for Parabolic Reflector at 40 kHz.

4. <u>Glass Reinforced Plastic (GRP) Dome Transmission Tests</u> – With the proposed installation at the top of the SURTASS LFA source array, a new towbody needed to be developed. This towbody included a custom fiberglass window that must be acoustically transparent. Air pockets or other flaws introduced in the manufacturing process would make the fiberglass reflective. Previous tests on fiberglass panels have shown that this material can meet the acoustic characteristics requirements if fabricated properly. The fiberglass window was fabricated by a vendor chosen by NFESC. As a quality control measure on the manufacturing process, transmission loss tests were conducted with the objective of determining the transmission loss of a prototype fiberglass panel.

a. <u>Testing Method</u> - A fiberglass panel 39 inch x 39 inch x 5/32 inch was provided by NFESC and was tank tested. The tank is approximately 2.4 m (8 ft) in diameter and over 1.2 m (4 ft) deep. The sheet was attached to the rotator and submerged in the center of the tank. The source was an ITC hydrophone suspended 25.4 cm (10 in) from the plate at a depth approximately equal to the plate center. The receiver was a B&K hydrophone and was suspended 22.9 cm (9 in) from the plate on the opposite side at the same depth as the source. Sine wave bursts at 30, 35, and 40 kHz were emitted and the transmitted signal captured at the receiver. Source levels were monitored to ensure consistency.

The first test was performed with no panel, and the received signal was used as a baseline to compare transmission loss through the panel. The signal length was adjusted so that only the direct path was captured in the time window. After the panel was inserted, the process was repeated for incidence angles ranging from 0-60 degrees. Finally, the panel was removed, and the test was performed again to verify that there was no change in the geometry of the system.

b. <u>Analysis</u> - The transmission loss was calculated by comparing the received levels with and without the panel. A Tektronix TDS360 oscilloscope computed the rms levels for the direct path, using the average of eight pings. Since the source level and medium loss were the same for all tests, these factors were ignored, and the transmission loss was measured directly from the received signal. It is given by:

$$TL = 20 \log 10 \left(P_{RMS,no\ panel} / P_{RMS,\ panel}\right);\ \text{where } P = \text{panel received level.}$$

c. <u>Results</u> - The fiberglass had transmission losses of less than 1.5 dB at normal incidence, and lower losses at higher grazing angles. Figure B-20 shows a plot of the transmission loss versus incidence angle for the three frequencies. Figure B-21 shows a comparison with previous tests. The other tests were at 37 kHz, and with panels of different thickness (1/4 inch and 1/8 inch). Both 35 and 40 kHz tests for the present panel are shown for comparison.

d. <u>Conclusions</u> - The manufacturing process for the fiberglass is acceptable. Transmission losses were similar to previous measurements of other fiberglass panels.

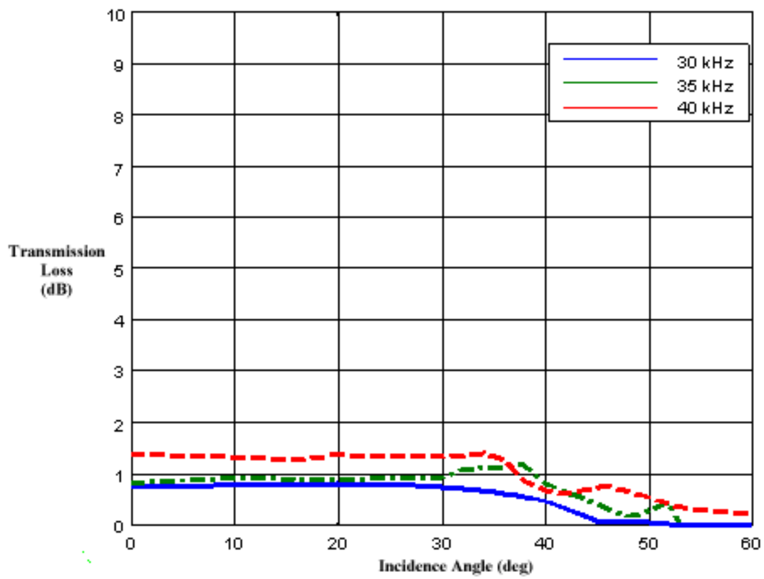


Figure B-20. Fiberglass Transmission Loss Curves versus Incidence Angle for Frequencies 30-40 kHz

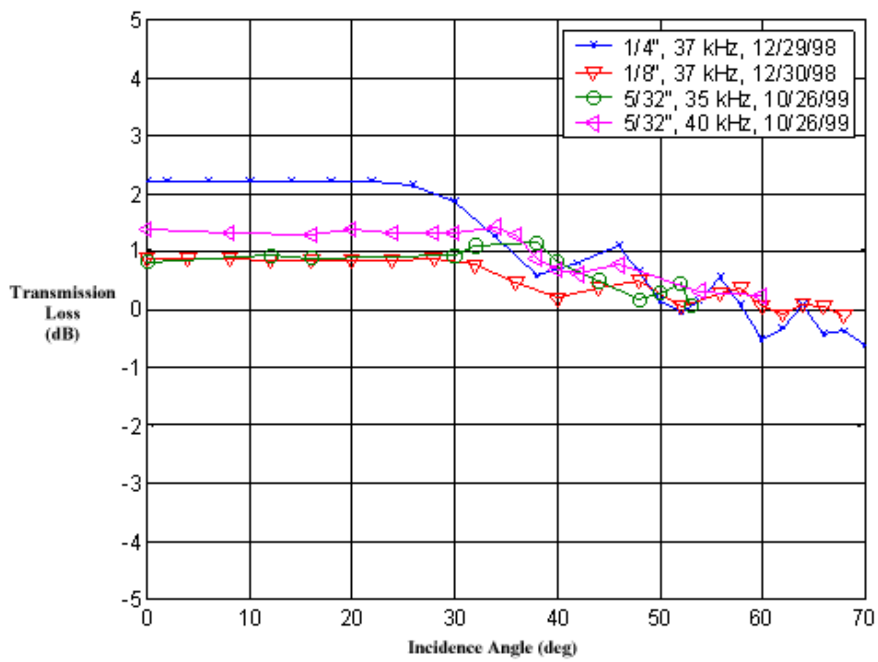


Figure B-21. Transmission Loss Curves for Previous Tests of Fiberglass Panels.

5. Trials on R/V *Cory Chouest*, FY00 - As of November 1999, the HF/M3 sonar design had successfully progressed through several critical stages of development. This included concept formulation, in-water testing of a single source/receiver (S/R) unit at the NUWC Test Facility at Seneca Lake, NY, and a full-up system test in Baja, Mexico, in March/April 1999. Remaining tests included the HF/M3 sonar towbody tests and the sonar system performance trials. The towbody test was conducted off the R/V *Cory Chouest* out of Hawaii in December 1999. The results are discussed in subsection (a) below. Sonar system performance trials for Spring 2000 onboard R/V *Cory Chouest* are discussed in subsection (b) below.

a. Sonar Fairing Body Tow Tests - The objectives of the December 1999 towbody tests were to:

- Observe and record the hydrodynamic behavior of the HF/M3 towbody as part of the LTS Array.
- Observe and record the hydrodynamic behavior of the LTS Array, specifically the possibility of any changes in the array behavior due to the addition of the HF/M3 system.
- Verify a complete and successful mechanical integration of the HF/M3 system into the LTS Array and into the LTS Handling System.
- Evaluate overall mechanical integrity of the HF/M3 system.

Detailed results of this test are provided in a seperate report[23]. The hydrodynamic behavior of the LTS array during this tow test was consistent with previous results. Comparison of previous cone angles to the cone angles measured during this test confirmed that integration of the HF/M3 unit into the LTS array had negligible influence upon the hydrodynamic behavior of the LTS array.

At a ship speed of 3.0 knots the HF/M3 system displayed particular characteristics. The body pitch had a mean value of 0.57 degrees (nose down) and a standard deviation of 0.28 degrees. The body roll had a mean value of 2.27 degrees and a standard deviation of 0.40 degrees. There is a small random variation in the towbody roll, increasing with an increasing speed of the towbody. Tightening up the play in the roll restraint solved the problem.

During the Spring 2000 trials, ship speed, body pitch and body roll data were again recorded to verify the results obtained during the December 1999 tow test, and to obtain more accurate speed data.

During testing, the towbody and associated suspension hardware proved to be of sound design. There were no failures of the towbody components or suspension hardware. The towbody also proved to integrate with the handling system with no complications. Initially, some modifications were required for clearances of the towbody in the centerwell, but these modifications proved to be sufficient.

---

[23] Naval Facilities Engineering Service Center. "HF/M3 Tow Test Onboard M/V *Cory Chouest*: Summary Report." 27 January 2000.

b. <u>System Performance</u> – Qualitative and quantitative assessments of the system's ability to detect marine mammals of various sizes have been verified in several sea trials (Table B-6). Appendix A presents detailed descriptions of measured and predicted performance estimates of the HF/M3 sonar. In roughly 170 hours of at-sea testing with artificial targets, six whales have coincidentally been spotted on the surface after strong detections were made in the same general vicinity on the HF/M3 system. Approximately 75 other objects have been detected during testing, which were believed to be marine mammals.

Table B-6
HF/M3 Sonar Testing

Date	Testing	Location
October 1998	Performance testing of single source/receiver.	NUWC, Seneca Lake, NY
April 1999	Performance testing using complete prototype.	Baja California
February 2000	Calibration of system.	NUWC, Seneca Lake, NY
April 2000	Integration with LFA array on R/V *Cory Chouest.* Engineering trials following installation.	Hawaii
May 2000	Performance testing (HF/M3 sonar only) on R/V *Cory Chouest.*	Hawaii
August 2000	Performance testing with controlled bottlenose dolphins.	Southern California
October 2000	Marine mammal mitigation trials.	Adriatic Sea

For large animals swimming within 200 m (656 ft) of the surface, system performance is relatively insensitive to animal dive patterns and numerous detections are likely before the animal enters the LFA mitigation zone. Single-ping false alarm rates can be held to approximately 1 per 10,000 pings under these scenarios. The ability to track animals via multiple detections virtually eliminates randomly distributed false alarms. The most challenging scenarios are those aimed at detecting small, solitary, fast-diving animals (i.e., moving vertically through the HF/M3 detection zone) in environments with high-clutter characteristics (e.g., shallow water, downward-refracting water column, high sea states).

A dedicated experiment designed to verify the system's detection ability using bottlenose dolphins was conducted off the coast of San Diego in August 2000. This proved to be one of the most challenging possible scenarios, as the tests were conducted with small odontocetes diving vertically through the LFA mitigation zone, in shallow (300 m [984 ft]), downward sound-refracting waters that produced a significantly more acoustically cluttered environment than would be expected under normal SURTASS LFA sonar operating conditions. Trained bottlenose dolphins (U.S. Navy MK7 marine mammal system) were commanded to dive one at a time to moored objects 130 to 200 m (426 to 656 ft) below the surface and return, with the HF/M3 system positioned 400 to 1,000 m (1,312 to 3,280 ft) away.

Eleven out of a total of twenty dolphins were detected by the HF/M3 sonar. Given these results, the following factors must be considered for these tests:

- Tests were conducted in a shallow-water, downward sound-refracting environment.
- The bottlenose dolphins had a low target strength (-13 dB).
- Operating from their handlers' boats, the dolphins did not enter the area from outside the LFA mitigation zone. Instead, the dolphins dove and surfaced vertically through the ensonified region; therefore, they were within the HF/M3 detection envelope for a very short time.
- Environmental conditions during these tests reduced probabilities of detection significantly in comparison to deep-water scenarios (normal SURTASS LFA sonar operations), where system settings (primarily transmitted waveform parameters and projector tilt) can be optimized.
- HF/M3 search zones will typically be at deeper depths than those focused on during these tests, also serving to increase probabilities of detection via advantageous thresholding adjustments to lower clutter fields.

It should be noted that even for this extremely challenging scenario, the detection rate was 55 percent for a single ping. This is higher than the 50 percent value that was used in the SURTASS LFA Sonar OEIS/EIS for "active acoustic monitoring" in the calculation of an overall effectiveness estimate for monitoring mitigation.

c. <u>Summary of Statistical Performance</u> - The probability of detecting an animal in the vicinity of the SURTASS LFA sonar depends on several factors, including the single-ping probability of detection, animal behavior, and the HF/M3 sonar scan rate. The single-ping probability of detection used here is defined as the probability of detecting an animal present within the HF/M3 sonar scan beam as a function of range using a single ping.

Figure B-22 shows the single-ping probabilities of the HF/M3 sonar detecting various marine mammals as a function of range. These curves are based on: 1) The in situ measured interference (i.e., backscattering and false targets that cause target-like echoes on the sonar) observed during the August 2000 testing; 2) The in situ measured transmission loss (TL) from the August 2000 testing; and 3) The best available scientific data on marine mammal target strength (i.e., the expected ability of a marine mammal to "reflect" acoustic energy) (See Appendix A). Again, it should be noted that the August 2000 testing occurred in an extremely challenging underwater environment (i.e., shallow water, small and fast targets, high reverberation, and downward-refracting sound propagation), and that deep-water operations would be expected to have higher probabilities of detection for all species at all ranges.

The measured results of the August 2000 testing correspond well with the curves presented in Figure B-22. For a nominal 800 m (875 yd) range (actual test ranges from the HF/M3 sonar to the dolphins were 366 to 914 m [400 to 1,000 yd]), a probability of detection of 55 percent was observed. The 2.5 m dolphin curve of Figure B-22 shows a probability of detection of 55 percent at 930 yd (850 m).

The single-ping probabilities of detection show one facet of the effectiveness of the HF/M3 sonar as a mitigation tool because, in general, any marine mammal that enters the HF/M3 detection zone can be expected to be ensonified multiple times approximately once every 50 seconds. The number of potential detections depends on the course, speed and depth of the animal in relation to the HF/M3 sonar beam patterns.

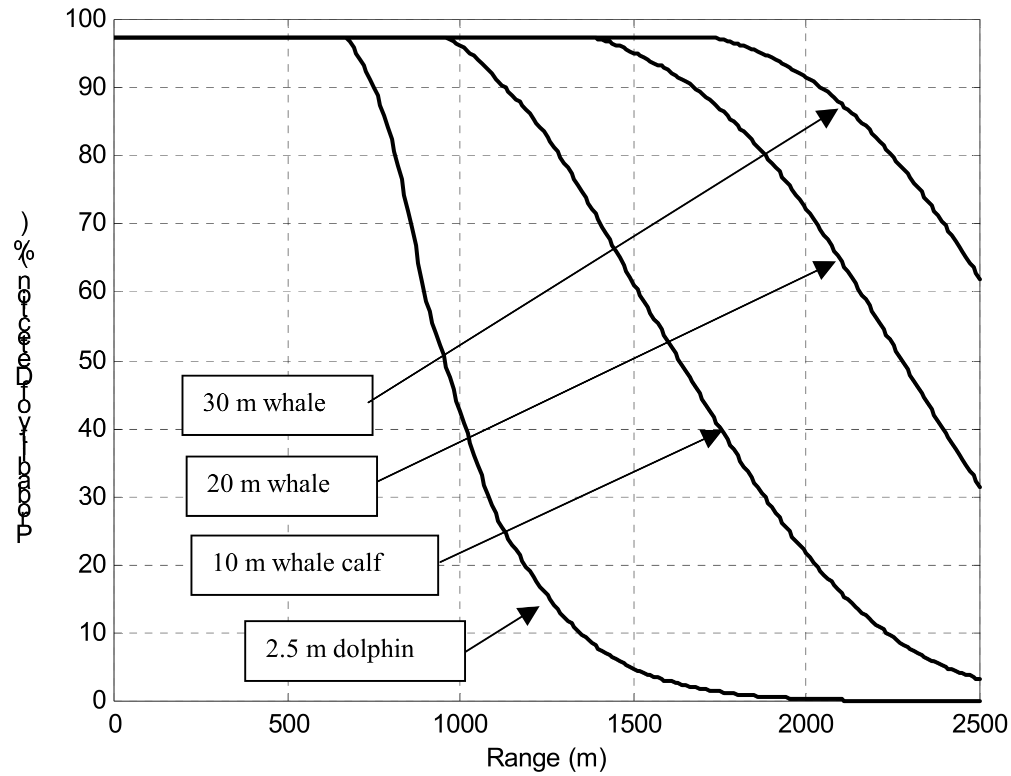


Figure B-22. Probability of Detecting (on any given ping) Various Marine Mammals Swimming within the Search Beam of the HF/M3 Sonar System.

A realistic scenario that would present a short time period for the animal to be within the HF/M3 detection zone before it entered the LFA mitigation zone would be an animal forward of the SURTASS LFA ship moving toward it. This effectively combines the ship's and the animal's velocities. If the ship is traveling at 1.54 m/s (3 kts) and the animal swims toward the SURTASS LFA sonar at 2.6 m/s (5 kts), it will remain in the 1 to 2 km-radius (3,280 to 6,560 ft) annulus surrounding the HF/M3 sonar long enough to be ensonified approximately 5 times.

From Figure B-22, it can be seen that for a 2.5 m dolphin, Pd_1 (at 1,000 m) = 43 percent. Using the formula $Pd_N = 1- (1 - Pd_1)^N$ [24], where N = number of animal ensonifications and Pd_1 = the single-ping probability of detection, it can be seen that for 2 ensonifications, $Pd_2 = 1 - (.57)^2 = 1 - 0.32 = 68$

---

[24] Department of the Navy (DON). 1998. Shock testing the seawolf submarine. Final environmental impact statement, May 1998. Department of the Navy, Southern Division, Naval Facilities Engineering Command, North Charleston, SC.

percent. For 4 ensonifications, probability of detection increases to 90 percent, and for 5 ensonifications, probability of detection approaches 100 percent.

Animal depth can also be addressed using similar probabilistic methodology as was employed to generate Figure B-22. It is assumed that the LFA mitigation zone can be generally represented as a disk with its vertical dimension from approximately 80 m (262.5 ft) to 160 m (525 ft) depth, extending out to a radius of approximately 1 km (0.54 nm) (see Figure A-1).

Probabilities of detection for a stationary whale of 20 m (66 ft) length (e.g., a humpback) at various depths and ranges within the LFA mitigation zone are estimated to be from 98 percent (animal at 1 km (0.54 nm) range and 160 m (525 ft) depth) to 72 percent (animal at 2 km [1.08 nm] range and 160 m (525 ft) depth). Outside of the LFA mitigation zone, probabilities of detection for the same whale are estimated to be from 95 percent (animal at 1.5 km [0.81 nm] range and 200 m [656 ft] depth) to 35 percent (animal at 500 m [1,640 ft] range and 40 m [131 ft] depth). Thus, an animal of this size approaching the LFA mitigation zone from any direction would have an extremely high likelihood of being detected before entering the zone.

The remote possibility exists that a deep and long-diving animal (e.g., sperm whale family, beaked whale family) could approach the LFA mitigation zone without being initially detected by the HF/M3 sonar. It could swim from deep depth upwards into the LFA mitigation zone between HF/M3 sonar beam scans. However, for this to happen, the animal would have to surface within 1 km (0.54 nm) of the SURTASS LFA vessel where it would readily be detected by the HF/M3 sonar and most likely visually detected (during daylight hours). For example, the probability of HF/M3 sonar detection of a 20 m (66 ft) whale within 1 km (0.54 nm) is greater than 95 percent. Additionally, using a nominal 15 percent duty cycle for the SURTASS LFA sonar, even if an animal were to avoid the HF/M3 sonar and enter the LFA mitigation zone in this manner, there would be only a 15 percent (i.e., 1 in 6) chance that SURTASS LFA sonar would be transmitting while the animal was in the zone, before it was detected.

C. SYSTEM DESCRIPTION

1. <u>System Components</u> - The HF/M3 sonar system is a modular design with key modular elements located at the top of the SURTASS LFA sonar source array and in the SURTASS Operations Center (SOC). The towbody, which houses the HF/M3 sonar source/receiver, is located above the LTS junction box in the area currently occupied by a finned spreader bar. The HF/M3 system shares the LTS umbilical cable, using 2 fiber-optic channels and 4 #8 copper conductors. Electrical and data signals are broken out of the LTS junction box and routed to the HF/M3 system by way of a faired cable harness. Shipboard topside equipment includes a 2 kVA power amplifier, a DC power supply, a Pentium IIIe personal computer, an RS-485 fiber optic modem and a fiber optic data-link receiver. Figure C-1 provides a diagram of the HF/M3 sonar key components.

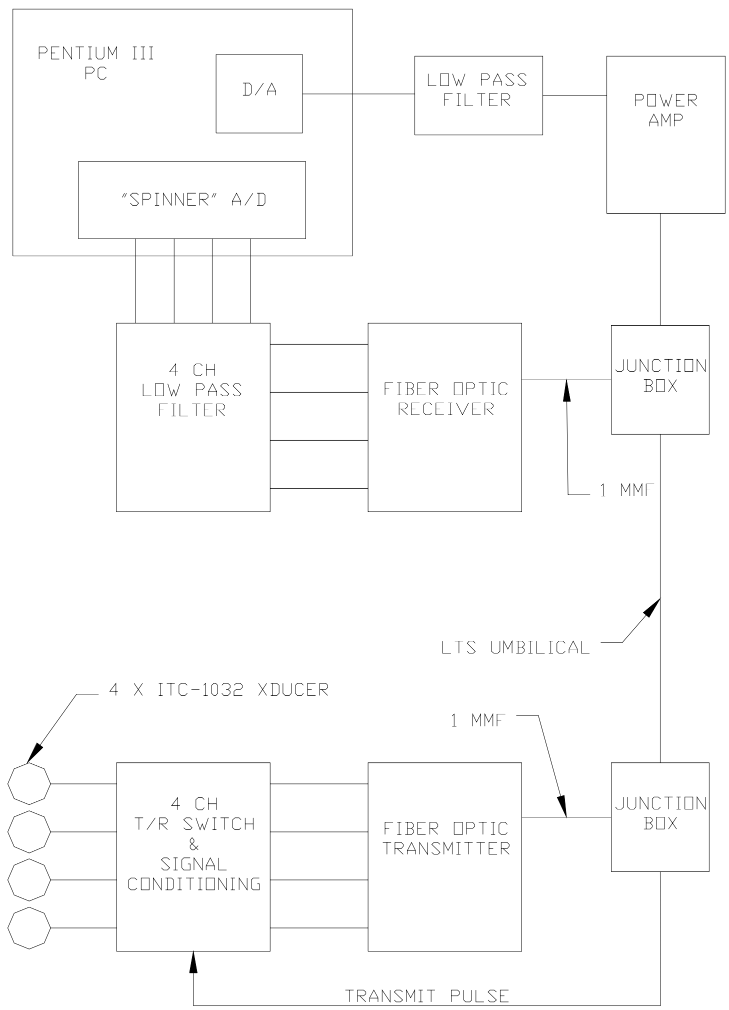


Figure C-1. Key Components of HF/M3 Sonar System.

a. Towbody - The HF/M3 towbody was designed to be integrated into the LTS Array. The towbody's purpose is to house the HF/M3 parabolic projectors, drive system, and associated electronics. The towbody was designed to be a stable, level platform under tow between the speeds of 2-5 knots at operating water depths of to 213 m (700 ft). The towbody weighs approximately 383 kg (845 pounds) in air and 277 kg (610 pounds) in water (not including projectors or electronics). Figure C-2 is a computer aided design (CAD) generated drawing of the towbody showing the three orthographic views and overall dimensions.

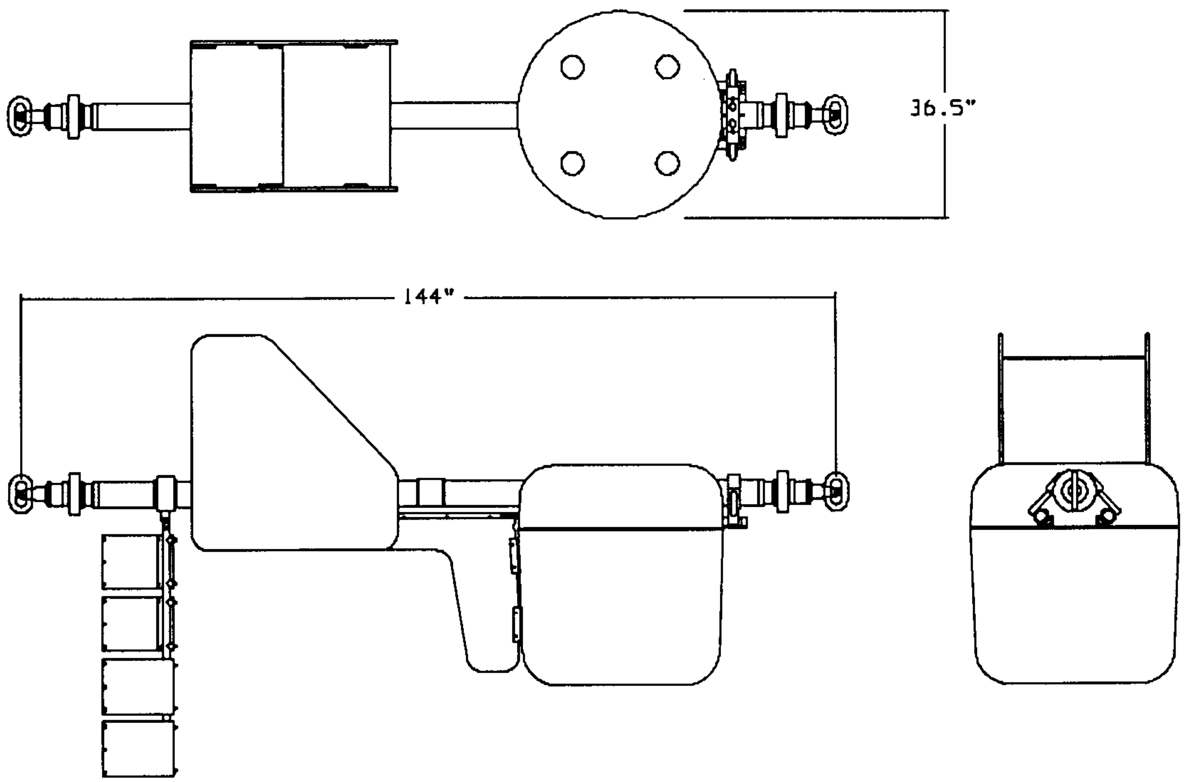


Figure C-2. HF/M3 Sonar Towbody, Orthographic Views.

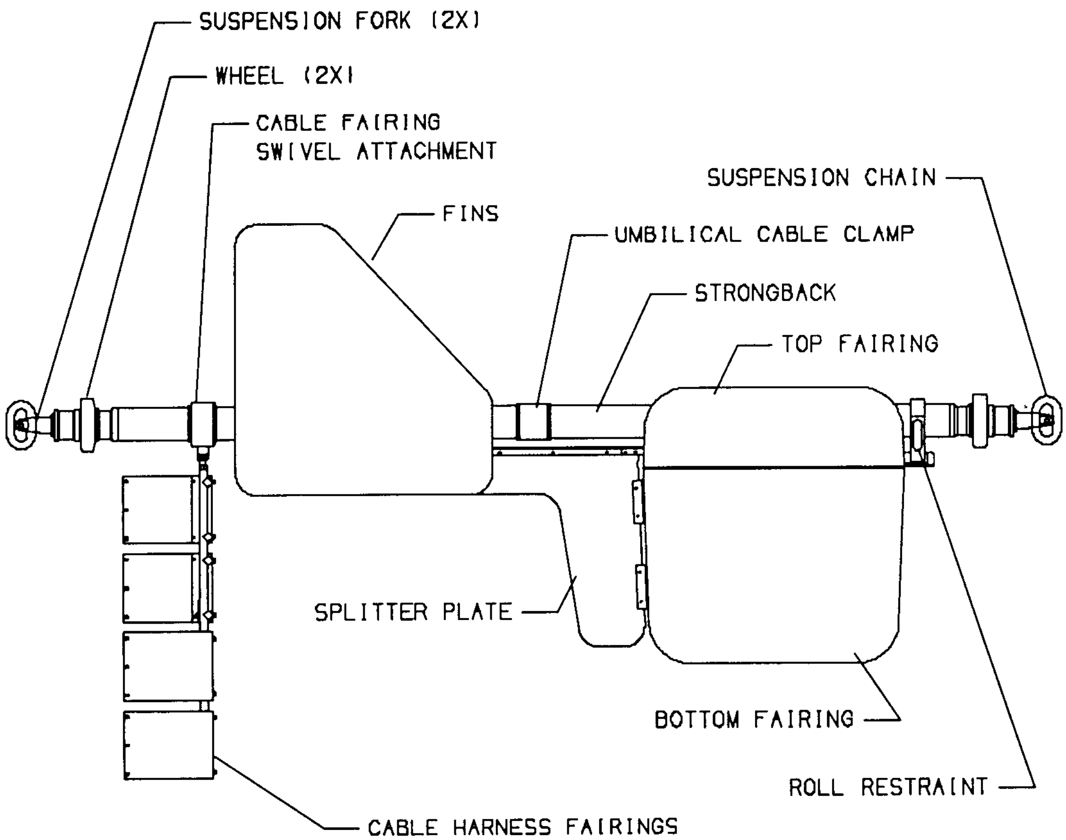


Figure C-3. HF/M3 Sonar Towbody Components.

Figure C-3 illustrates some of the general components that make up the HF/M3 sonar towbody. Figure C-4 is a photograph of the towbody sitting on its stands strapped to a trailer for transportation.

Figure C-4. Photograph of HF/M3 Sonar Towbody on Storage Stands.

A brief description of the general components is given here.

i. <u>Suspension Chain</u> - The suspension chain suspends the towbody in the LTS Array. (Also, see Figure C-5). The chain is 1-1/8 inch ORQ studlink anchor chain.

ii. <u>Strongback, Suspension Forks, Roll Restraint</u> - The strongback is a pipe that runs the length of the towbody and is the weight-bearing member. The strongback is stainless steel and is fixed to the suspension chain through the suspension forks. All remaining components of the towbody can rotate about the strongback unless the roll restraint is engaged. The ability for the towbody to roll is a requirement based on the shipboard handling system. The roll restraint is engaged after the towbody has been deployed from the handling system. The roll restraint is required to maintain a level platform under tow.

iii. <u>Wheels</u> - Wheels are mounted on the ends of the strongback and are used to support the towbody in the handling system storage tracks.

iv. <u>Cable Harness Fairings, Cable Fairing Swivel Attachment</u> - The cable harness fairings are the flexible conduit for the power and signal cabling between the towbody and wet side junction box. (Also, see Figure C-5.) The cable fairing swivel attachment is the interface between the cable harness fairings and the strongback.

v. Fins - The fins help stabilize the towbody and the array under tow, and are made of G-10 fiberglass plate.

vi. Umbilical Cable Clamp - The umbilical cable clamp is an attachment point for the umbilical cable as it passes the towbody. The umbilical cable carries the power and signal wires for the array and the HF/M3 system. The umbilical cable terminates in the wetside junction box. (Also, see Figure C-5)

vii. Splitter Plate - The splitter plate helps attach the projector-housing portion of the towbody to the fins so they can rotate as a unit. The splitter plate also helps separate turbulent fluid flow on either side of the projector housing to help minimize drag and increase towbody stability. The splitter plate is made of G-10 fiberglass plate.

viii. Bottom Fairing, Top Fairing - The bottom fairing makes up the projector housing and the top fairing houses the projector electronics. The fairings are made of hand-laid fiberglass cloth and mat in a polyester resin.

Figure C-5 is an illustration of the HF/M3 sonar towbody integrated into the LTS Array as configured for the R/V *Cory Chouest*. This figure represents only the top portion of the LTS Array, showing the first LTS module (18 total) at the bottom of the illustration.

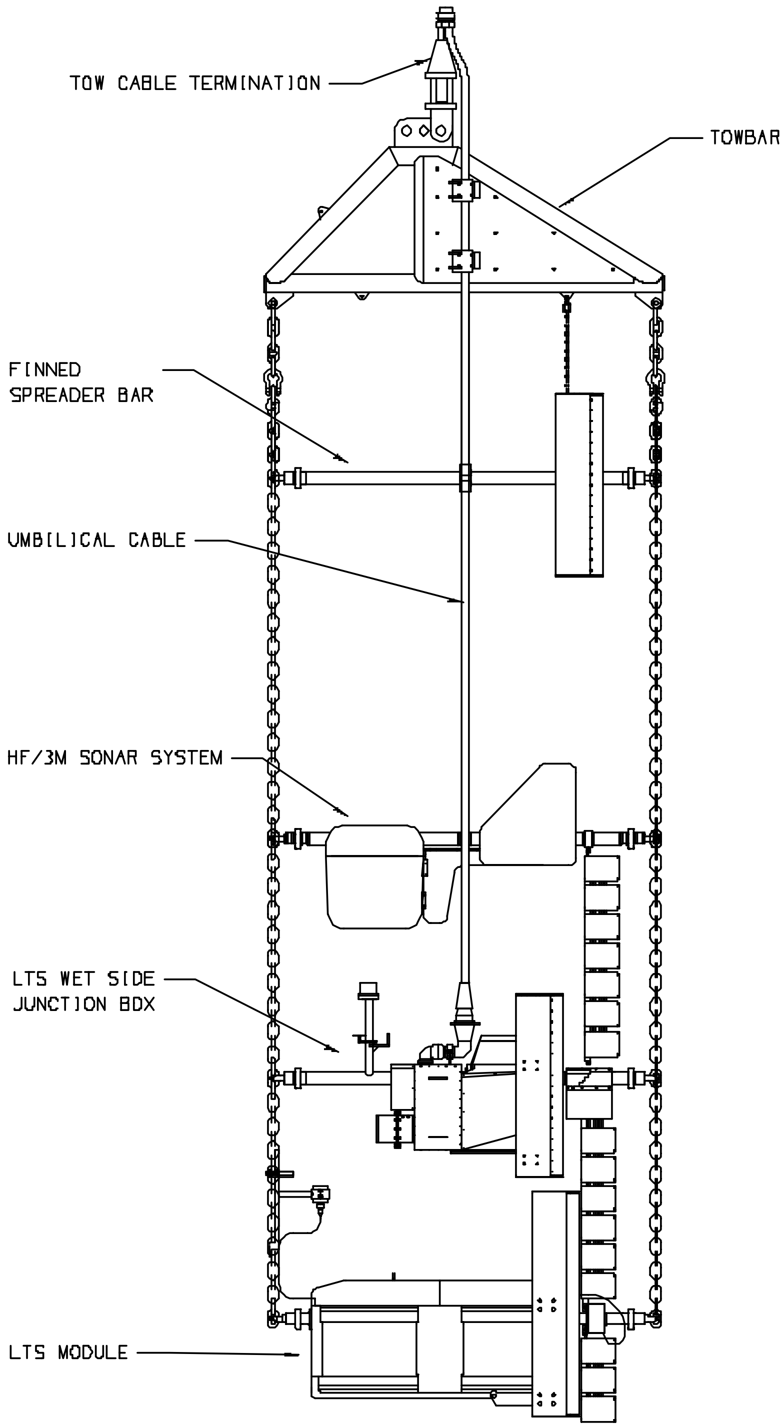


Figure C-5. Top Portion of LTS Array with HF/M3 Sonar System.

b. Source-Receiver Unit - The sonar itself consists of 4 omni-directional transducers mounted in parabolic reflectors, as shown in Figure C-6. The reflectors provide a 10 degree vertical beamwidth, an 8 degree horizontal beamwidth, and a nominal 20 dB directivity index. The transducers are mounted on a rotating carousel driven by a stepper motor. The vertical aim of the reflectors is adjustable between ± 10 degrees from horizontal. The rotating assembly and the associated electronic and electrical equipment are housed in a cylindrical fiberglass canopy fairing 91.4 cm (36 in) in diameter and 99 cm (39 in) high. The mounting structure for the fairing shells is a stainless steel plate, which is suspended on bearings from a strongback pipe, allowing the assembly freedom to roll, as shown in Figure C-3. The strongback attaches fore and aft to the LTS suspension chains. A tailfin assembly mounts on the strongback behind the HF/M3 transducer canopy. The entire HF/M3 module weighs approximately 522 kg (1,150 pounds) in air and 363 kg (800 pounds) in water.

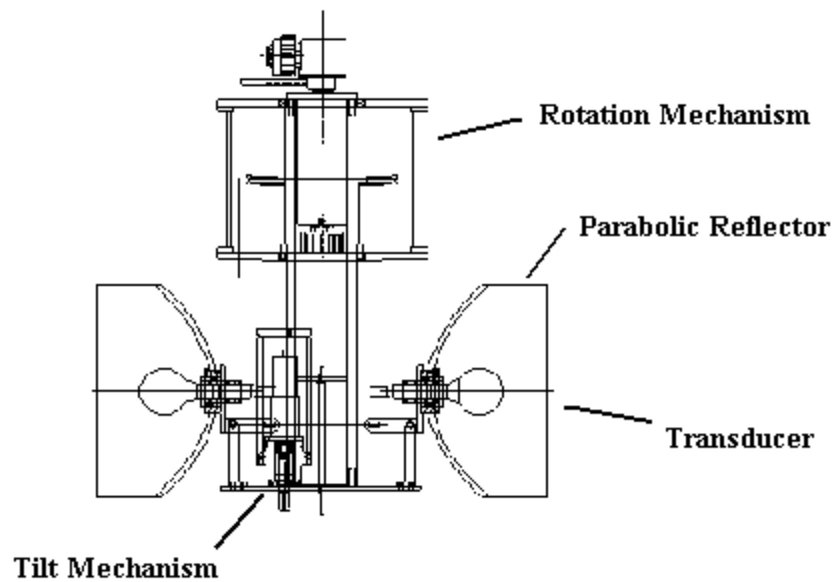


Figure C-6. Omni-directional Transducers Mounted in Parabolic Reflectors.

c. Signal Flow - The essential components of the HF/M3 system involved in the transmit/receive cycle are shown in Figure C-1.

The key steps in the signal generation and processing cycle are provided below:

1. Topside PC signals towbody PC to align Channel 1 for transmit.
2. Towbody PC closes T/R switch for Channel 1 and indicates to topside PC.
3. Topside PC sends transmit pulse through D/A output.
4. Topside PC signals towbody PC to align Channel 2 for transmit.
5. Towbody PC releases Channel 1, closes T/R switch for Channel 2 and indicates to topside PC.
6. Topside PC sends transmit pulse through D/A output.
7. Steps 4 - 6 are repeated for Channels 3 and 4.

8. Topside PC processes sonar echo signals for a range-dependent time interval (up to 4 seconds). Towbody PC is a montitoring and recording depth sensor and body pitch, roll, and yaw sensors.
9. Topside PC requests rotation of transducer carousel.
10. Towbody PC commands stepper motor controller to execute carousel rotation.
11. Carousel stops at new azimuth position and sequence is repeated.

d. Processor/Display Unit - A PC104 format 486 computer located in the HF/M3 towbody performs control and data acquisition functions as prompted by the primary system PC located topside in the SOC. An RS-484 serial communications link is provided over one fiber-optic channel. The PC104 system selects each of the 4-transducer channels sequentially for transmit. The receive signals are collected on all 4 channels simultaneously. A fiber-optic transmitter puts the 4 data channels on a single fiber-optic channel in digital format using time division multiplexing. A fiber-optic receiver located topside in the SOC converts the digital information back to 4 channels of analog data.

2. Operations Concept - The overall concept for operating the HF/M3 sonar as a mitigation sensor in support of the SURTASS LFA sonar is that of an autonomous stand-alone sonar system that requires minimal hands-on operation until a qualifying detection is made on the system. A qualifying detection is one that exceeds or is expected to exceed the established criteria for a potential marine mammal detection. These criteria will be preset for any given operating area, and will be based on locally modeled TL (using measured SVPs), SNR, DT and expected FAR as previously defined.

a. Sequence of HF/M3 System Setup Requirements – The HF/M3 sonar setup and operational requirements are defined below for each stage of its operation, from in-port to full mitigation operations.

i. In-Port, Pre-Operations - Prior to any SURTASS LFA sonar operations, the HF/M3 sonar must be groomed to good working order, including calibration of all components. All assigned personnel must be trained in its operation and maintenance while at sea. Finally, adequate spares and repair equipment must be onboard.

ii. At-Sea, Pre-SURTASS LFA Sonar Operations - The mitigation range for the SURTASS LFA sonar operations is the 180-dB sound field. HF/M3 sonar operating parameters will be based on a combination of in situ modeling and probe pulse results. Low Power (SL<180 dB) HF probe pulses will be used to determine the most effective vertical steering angle for the HF/M3 sonar. This entails a trade-off between near-surface tracking capability and surface clutter reduction. Establishing the operational WF and range-of-the-day will be determined from in situ modeling and probe-pulse results. HF/M3 sonar start-up mitigation will occur prior to full power HF/M3 sonar operations. A 5-minute ramp-up will ensure there is no inadvertent exposure of local animals to received levels in excess of 180 dB re 1 μPa (rms). If the operating area is found to be clear, the SL will be increased in 10 dB steps until full power (if required) is achieved. At this juncture the operator will verify the probe pulse steering and surface clutter results at full power and adjust as necessary.

iii. SURTASS LFA Sonar Start-up System - Existing U.S. Navy-approved SURTASS LFA sonar procedures and requirements for start-up will be followed.

iv. <u>At-Sea SURTASS LFA Sonar Operations</u> - The HF/M3 sonar will commence operating 30 minutes prior to SURTASS LFA sonar first transmission and continue until transmissions are terminated. The HF/M3 sonar PC control station will be unmanned during normal operations, but a remote display will be situated within view of the SURTASS LFA sonar watch supervisor. The HF/M3 ping sequence, HF WF choice, and HF PC display and signal processing set-up will be based on the sequence of start-up tests and procedures described. Detection of a target within the range of the HF/M3 system (nominally expected to be on the order of 2 km (1.1 nm) or greater) will trigger a display alert (visual/acoustic or both) to SURTASS LFA sonar watch personnel. An interim HF/M3 tracking team will be established to evaluate the detection alert.

v. <u>HF Tracking Team</u> - When the HF/M3 sonar triggers an alert, the tracking team will make an immediate assessment of the situation and take appropriate action in accordance with detailed guidance. If the detection appears to not be a false alarm and is near or within the SURTASS LFA sonar mitigation range, consideration must be given to shutting down the LTS source array. This decision will be based upon a logical decision process similar to that for classifying detections on the SURTASS LFA sonar. The decision process will include such data as expected FAR statistics, SNR, M-of-N, energy density, established track, etc.

If the projected track of the detection is well outside of the 180-dB LFA mitigation zone, SURTASS LFA sonar operations will continue. However, the tracking team will continue to monitor the track until the animal is beyond the detection range of the HF/M3 sonar. If the projected track of the animal falls within the mitigation zone, the SURTASS LFA sonar source will be shut down prior to this zone being entered. SURTASS LFA sonar operations will be resumed 15 minutes after the track shows that the target has exited the LFA mitigation zone, or there is no further detection of the target within the zone.

b. <u>Detection and Classification</u> - The HF/M3 sonar system is intended to be operated in a low clutter environment. This attribute derives from several design features:

- Operations will generally be at depth (order of 91 m (300 ft) (or more)) with a steerable 10-degree vertical beam keeping energy away from the surface and bottom.
- Very high rejection of potential clutter from sidelobe energy, both on transmit and receive.
- Adaptable range-dependent normalization, restricting nearby, very low TS targets from cluttering the screen display.
- Ongoing developments such as: 1) M-of-N clutter rejection, and 2) Enhanced screen tools allowing for more rapid display cleansing.
- Detections will be enhanced by the very low beam noise environment. A Directivity Index (DI) on the order of 20 dB is achievable in the already low noise regime around 30 kHz.
- Detection ranges will be limited in most cases by two-way transmission loss, and especially its absorption component, which rises rapidly with both frequency and range.

The excellent potential for low-clutter operations in an operational environment was demonstrated on the Baja trials, as depicted by Figure B-10. The detection results provided on this screen represent not only the artificial targets and local whales, but also approximately twenty pings' worth of accumulated reverberation and clutter. The absence of any obvious clutter after this lengthy accumulation process is a strong indication of the system's design capability for low clutter if operated as intended.

Understanding and accurately predicting the detection and tracking capabilities of the HF/M3 system will be an inherent part of the classification process with the HF system. Because of the relatively short operating ranges (order of a few km) of such a system, its capabilities can be accurately modeled once a good sound velocity profile (SVP) has been measured. The key steps in the detection and tracking process include:

- Setup - Understanding the environment and setting up the system for optimum capability. In simple terms, this can be accomplished with a measured SVP, a good propagation model, and a series of probe pulses to interrogate the clutter and noise characteristics of the operating environment. The results from these probes will show the potential for near-surface detections, and expected SNR of any biological targets.
- Wavetrain (WT)/Waveform (WF) Selection – The HF/M3 system uses a swept sinusoid signal. WT selection consists of choosing the start and stop frequencies and hence the bandwidth of the sinusoid and the time duration. Generally, a bandwidth of 6 kHz with a start frequency of 30 kHz is recommended.
- Threshold Criteria for detection – Threshold criteria depend on ambient noise and clutter and should be set at approximately 10 dB above the ambient noise or clutter (whichever is higher), but dependent on acceptable false alarm rates given the SURTASS LFA sonar operational scenario.
- Classification Guidelines – Primarily track established in association with other clues from visual and passive acoustics.

c. Training – The approach recommended for training Military Detachment (MILDET) personnel in the operation of the HF/M3 sonar is a hands-on demonstration method. The system is operated on a PC with a standard keyboard and mouse. The basic detection display and associated tools are especially straightforward for personnel with SURTASS LFA sonar operator's background. Personnel with mid-frequency or mine-hunting sonar experience will be especially well suited to the operation of the HF/M3 system. The ongoing development of the training syllabus is a two-part process associated with: 1) The initial installation, checkout and engineering trials of the HF/M3 system, and 2) Development and initiation of a structured training class for personnel to be assigned to HF/M3 duties.

i. Objectives – The primary objective of the operator training is to provide the operator with not only the skills to efficiently operate the system, but also a basic understanding of the underlying principles of the HF/M3 sonar operation, including:

- High frequency sonar beamforming and propagation, including absorption effects and resultant impact on range of detection.
- Marine mammal maneuvering and target strength.
- Time Motion Analysis (TMA) of high-bearing-rate contacts including track development and Closest Point of Approach (CPA) analysis.
- Tuning the system for optimum search and detection, including Environmental Acoustics (EVA) input, probe pulse analysis, use of vertical steering to minimize surface reverberation, and threshold detection settings.

ii. <u>Approach</u> – The first round of training occurred coincident with the installation and engineering trials of the HF/M3 system onboard R/V *Cory Chouest* in Spring 2000**.** Training included integrated periods of on-system training with lecture periods on the subjects described in the objectives. The first stage of training required a maximum of one day with a class size of one to six persons. The second stage of training occurred during at sea trials and operations. Actual target detection and tracking were available during these operations. Key personnel who will be charged with the HF/M3 sonar operation will undergo at sea training in a target-rich training environment that will help optimize their educational process. During this period, trainees will learn each of the techniques needed to accomplish the system operation objectives. Significant lessons learned have been recorded so far with respect to both actual HF/M3 sonar operations on R/V *Cory Chouest,* as well as the draft course syllabus.

The second round of training occurs when new personnel are assigned to HF/M3 sonar duties. As this occurs, personnel already assigned and experienced in its operation will accomplish their training. The training guide will continue to be the basic tool for this stage of training, but it is anticipated that lessons learned during actual operations will play an important role in updating and improving the training material.

iii. <u>Documentation</u> – A draft training syllabus for the HF/M3 system was prepared for initial use during the installation and trials period onboard R/V *Cory Chouest* in Spring 2000. This syllabus covers all aspects of the system operation, including supporting material for each of the training objectives cited above. Subsequently, updates taking into account lessons learned will be made to the syllabus and a revised text will be available prior to the next stage of SURTASS LFA sonar HF/M3 sonar operations.

D. LOGISTICAL SUPPORT

1. Supportability/Maintenance On Board - A support and maintenance procedures document has been delivered with the system**.** The HF/M3 sonar system has mechanically-steered apertures. It is anticipated that the only regular maintenance required aboard ship will be lubrication of the gear assemblies. Downloading and archiving of data might also be required. Long-term maintenance might require replacement of the gear assemblies. This is anticipated to be a depot-level overhaul.

The support document includes procedures for system failures. The HF/M3 sonar system will be comprised almost entirely of inexpensive COTS components. The low system costs will allow for 100 percent spares to be available onboard. The support and maintenance document describes procedures for identifying failed assemblies. A properly trained individual should be able to identify the failed component within 4 hours. Replacement of any failed component should take less than 2 hours.

2. Spare Parts Support - Table D-1 is a parts list for the HF/M3 sonar system. Spares of all major assemblies are available onboard for rapid replacement of any failed components. System down time should be no longer than a total of 6 hours. Depot-level repair will be accomplished by the original equipment manufacturer (OEM). The depot shall hold in inventory enough spare parts to repair any given components or assembly of the HF/M3 system within 1 week after receiving the failed component.

3. Depot Level Maintenance and Repair – Depot-level maintenance includes repair of any failed components. It also includes any required long-term overhauls of the mechanical components. The mechanical components are very robust and the wear, given the small rotation speeds, is expected to be very small. It is expected that depot-level overhaul will not need to occur for several years. However, this does depend on the number of hours of operation. System overhaul can be performed in a few days. Depot personnel shall also be made available aboard ship to support any issues involving the HF/M3 system within 72 hours of being requested.

Table D-1. HF/M3 Sonar Component List.

COTS Equipment

Item	Quantity	Manufacturer	Model
Fiber Optic Transmitter	1	Talbot Technology Corp.	FOA2T
Fiber Optic Receiver	1	Talbot Technology Corp.	FOA1R
Fiber Optic RS-485 Modem	2	Force, Inc.	Model 2844
Personal Computer	1	Dell	Dell Workstation 410
Monitor	1	Dell	Dell Ultrascan P1110
A/D Board	1	Bittware Systems	Spinner
D/A Board	1	National Instruments, Inc.	PCI-6713
RS-485 Serial Comm. Board	1	B&B Electronics	3PCISD1A
RS-232/RS-485 Converter	2	B&B Electronics	485LP9TB
Power Amplifier	1	Instruments, Inc.	S26-2
Linear Power Supply, 53.0 VDC	1	Acme Electric Corp.	750B48H
Voltage Step-up Autotransformer	1	Total Recoil Magnetics	
DC-DC Converter	1	Vicor	VI-RJN330-CXXZ
DC-DC Converter	1	Vicor	VI-MN3-CQ
DC-DC Converter	1	Vicor	VI-RJN220-CZZZ
Gear Motor	1	MicroMo Electronics	3557K024C-38/1-989:1+X0430
Stepper Motor	1	Parker Compumotor	RS33B
Stepper Motor Drive/Indexer	1	Parker Compumotor	OEM 750X
Spherical Transducer	4	International Transducer Corp.	ITC-1032
Digital Compass Module	1	Honeywell	HMR3000
Pressure Transducer	1	Setra Systems, Inc.	Model 207, 500PSIG
Electrical Slip Ring	1	Focal Technologies, Inc.	Model 180-0124-16
PC/104 Components:			
Analog I/O Module	1	Diamond Systems Corp.	Diamond-MM-32
DC-DC Converter	1	Win Systems, Inc.	PCM-DC/DC
Serial Comm. Module	1	Win Systems, Inc.	PCM-COM4A
PC/104 CPU Module	1	Win Systems, Inc.	PCM-SX
PC/104 Enclosure	1	Tri-M Engineering, Inc.	Can-tainer

Vendor Fabricated Parts

Assembly	Qty	SSI Drawing No.
Transducer Carousel	1	80100G1
Bearing Sleeve	1	80200G1
Stepper Motor Equipment	1	80300G1
PC/104 Equipment	1	80400G1
Analog Electronics Equipment	1	80500G1
DC Electronics	1	80600G1
Slip Ring Junction Box	1	80700G1
Tilt Motor Assembly	1	80800G1

APPENDIX A
High Frequency Marine Mammal Monitoring (HF/M3) Sonar System Performance Estimates

INTRODUCTION

This document presents measured and predicted performance estimates of the High Frequency Marine Mammal Monitoring (HF/M3) sonar system. The overall objective is to estimate the probability of both true and false detections under normal operating conditions. These estimates are provided for using a simplified receiver-operating-characteristic analysis. The steps taken in this approach are as follows:

- Perform parametric estimation of measured interference (masking signals) to generate a model of interference level probability distributions. The interference probability distributions are assumed to be range-dependent.
- Ensure that the derived statistical model of interference levels is conservative. In other words, demonstrate that the expected interference levels under normal operating conditions will not exceed those used to predict system performance.
- Verify ability to predict mean target echo levels and estimate second order statistical parameters (variance).
- Derive a thresholding scheme that satisfies criteria for target detection probabilities and false alarm probabilities.
- Use the derived interference and target statistical models in conjunction with the derived thresholding scheme to predict probabilities of false alarms and detections for various operating scenarios.

The approach adopted here has some limitations. Given the multitude of factors and random processes associated with interference levels and target echo levels, theoretical predictions of received levels are intractable. Therefore, derivation of interference and target echo level models specific to any given system must rely on measured data. The parameters defining these models can be modified for conditions that differ from those present during testing only when the effects of altering these conditions are well understood.

The range of waveform parameters (such as pulse bandwidth and temporal extent) for which the estimates provided here are valid, is limited to those used during data collection. In addition, the effects of varying environmental factors such as surface roughness and refraction can only be understood with a high degree of certainty for the range of conditions present during testing.

Exhaustive studies to reduce false alarms by studying their origins and discerning characteristics have yet to be fully carried out. Results from studies such as these, could lead to decreased false alarm probabilities. Several ad hoc techniques to classify possible detections as surface clutter have been implemented and lead to significant reductions in false alarms. We will not consider these discrimination techniques here in determining system performance, however, in order to maintain our conservative approach.

Review of System Specifications
The HF/M3 system is intended to detect marine mammals approaching and within a region of high sound pressure level associated with the LFA sonar. Figure AA-1 shows the specific dimensions and location of the LFA mitigation zone. The HF/M3 system resides approximately 70 m above the vertical center of the zone. The primary search range extends between 200 and 1000 m. Data indicate that animals will be detected before entering the region within 200 m of the LFA. We will therefore consider the primary search region to be the sub-area of the LFA mitigation zone extending laterally from 300 to 1000 m.

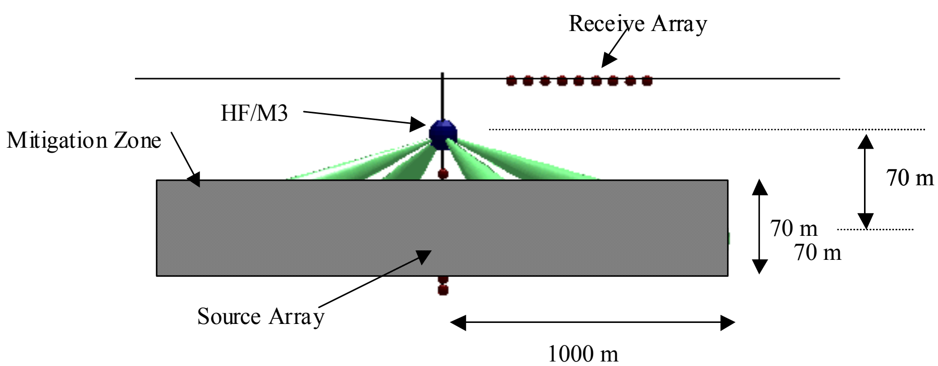
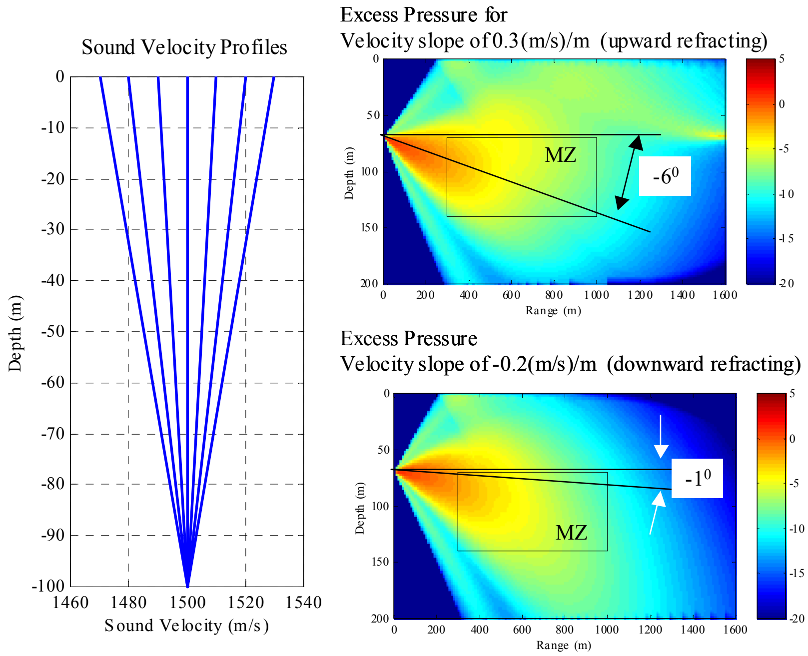


Figure AA-1. System concept and definition of the LFA Marine Mammal Mitigation Zone (MZ) (figure is not to scale).

The SURTASS LFA sonar is intended to operate above the main thermocline. It is therefore a reasonable assumption that the sound velocity profile local to the HF/M3 system will be predominantly linear (both upward and downward refracting cases are possible). Figure AA-2 shows the sound velocity profiles considered here. The optimal tilt setting of the system for a particular refractive environment is that setting which maximizes the average interrogating signal power within the LFA mitigation zone sub-area of interest. To illustrate this point, Figure AA-2 also shows the predicted excess pressure fields for two cases. A table summarizing the optimal tilt settings for those velocity slopes considered is also shown in the figure. Tilt settings which deviate from these optimum values (again, depending on the local sound velocity structure) will not be considered as normal operation conditions.



Velocity Slope (m/s)/m	Optimal Tilt Angle
0.3	-6.0^{0}
0.2	-5.5^{0}
0.1	-4.5^{0}
0.0	-3.5^{0}
-0.1	-2.5^{0}
-0.2	-1.0^{0}
-0.3	0.0^{0}

Figure AA-2. Potential sound velocity profiles, simulated spreading compensated transmission loss for two cases and optimal tilt settings for the various profile slopes and system depth of 70 m.

Summary of Results

The system's qualitative ability to detect marine mammals ranging in size from large whales to bottlenose dolphins has been verified in field trials. Despite the conservative measures taken in estimating system performance, predicted capabilities are quite good. In the 200-800 meter range, one false alarm is expected for every 350 azimuthal sweeps and detection probabilities for small to mid-size marine mammals within the LFA mitigation zone are typically no less than 90 percent. In the 800-1600 m range, one false alarm is expected every 25 azimuthal sweeps. The detection probability for small- to mid-size animals at distances of up to 250 m beyond the LFA mitigation zone is typically no less than 40 percent. For large marine mammals (e.g., whales) detection probabilities are typically greater than 90 percent at ranges extending up to 1 km beyond the LFA mitigation zone.

BACKGROUND

This section provides a brief background of the technical concepts utilized in deriving the system performance estimates[1].

Target Detection

Numerous random processes are associated with sonar target detection[2]. In addition to the random thermal noise inherent to system electronics and random background noise in the ocean, random fluctuations are introduced in signal transmission levels and phase. Acoustic backscattering from the rough ocean surface and even variably oriented targets are also random processes. The effects of these and other secondary random processes on the two primary

[1] R.J. Urick, *Principles of Underwater Sound*, 3rd Edition, Peninsula Publishing, Los Altos, CA, 1983.
[2] I. Dyer, "Statistics of Sound Propagation in the Ocean", J. Acoust. Soc. Am., 48, 337-345 (1970).

parameters associated with target detection, namely expected target echo level and expected interference levels, necessitate a statistical treatment of the predicted receiver output levels.

The probability density function (PDF) is used to predict the probability that a random variable falls between two values, which can be stated mathematically as:

$$P(a \leq X \leq b) = \int_a^b p(x)dx$$

where P (y) is the probability that event y will occur (here the event is that the random variable X falls between a and b) and p(x) is the probability density function of the random process. Figure AA-3 illustrates the statistical concept. Shown are conceptual PDFs of target echo level and interference level. Also shown is an arbitrarily selectable threshold. When the signal level at the sonar receiver exceeds this threshold a detection is obtained. The probability that this detection is associated with an actual target is equivalent to the area under the target echo level PDF to the right of the threshold. Conversely, the probability that the detection is due to interference is equivalent to the area under the interference-level PDF to the right of the threshold.

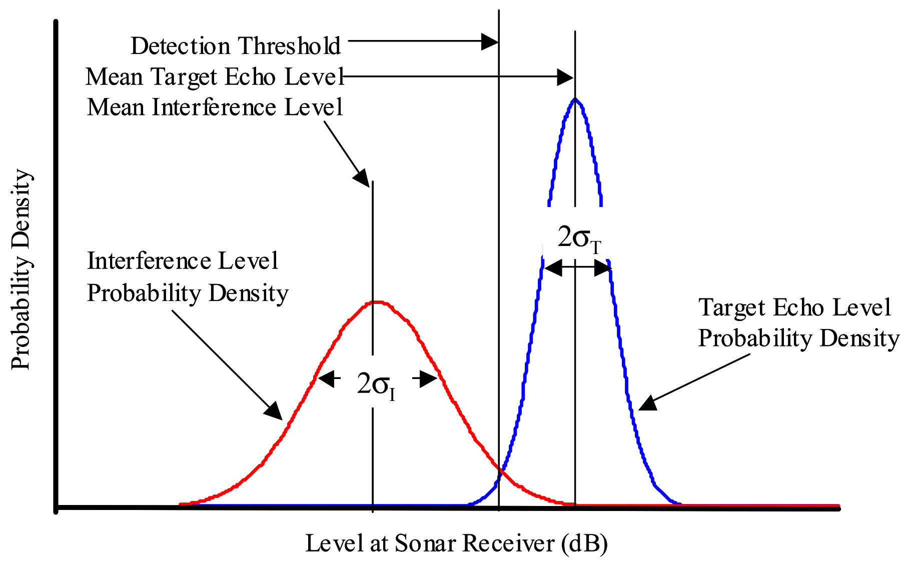


Figure AA-3. Illustration of target level probability density, interference level probability density and detection threshold.

The selection of a threshold level requires a trade-off between target detection probability and false alarm probability. A higher threshold decreases the probability of a false alarm yet decreases the probability of detection. Conversely, a lower threshold increases the probability of detection but at the same time increases the false alarm rate. We will rely on measured data to provide estimates of both the target and interference level PDFs.

Signal Processing

Selection of the transmitted waveform and processing that is performed on the received signals can be manipulated to aid in interference rejection and target acceptance. The HF/M3 system utilizes a frequency modulated (FM) sweep (or chirp) with center frequencies of 30-35 kHz, bandwidths (BW) in the 1500-6000 Hz range and pulse lengths in the 10-40 msec range. A matched (or auto-correlating) filter is used to effectively increase the signal-to-noise ratio and to minimize the surface clutter component of the interference.

Sonar Equations

The signal excess (SE) is defined as the signal-to-noise ratio at the receiver output (i.e., after matched-filtering). By specifying the processed echo level (EL) and interference levels (IL) in dB, we can write the following formula for SE:

$$\mathbf{SE=EL - ENL}$$

The processed echo power level is given by the following equation:

$$\mathbf{EL=SL - 2TL + TS + PG}$$

SL is the source level in dB (re 1μPa at 1 m) measured in the direction of the target, TL is the one-way transmission loss (in dB) due to a combination of geometric spreading and frequency dependent absorption, TS is the target strength (in dB), and PG is the waveform-dependent signal processing gain (in dB re $sec^{1/2}$). The target strength of several marine mammals is listed in Table AA-1. The TS of a particular species is considered to be that at head-on aspect. Given that the mean TS of a randomly oriented animal is somewhere between the maximum TS (broadside aspect) and the minimum (head-on aspect), our model for the expected mean echo level for a particular species is conservative.

Table AA-1. Summary of estimated target strengths of various marine species[3,4].

Length (m)	Broadside TS (dB)	Head-on TS	Species
30	15	9	Blue/Fin
20	11	5	Humpback
10	4	-2	Calf, Various
5	-2	-9	Pilot Whale
3	-8	-14	Beluga
2	-12	-18	Porpoise
1.5	-14	-20	Human/Seal

The effective noise level is the sum of the interference level (IL) and the detection threshold (DT):

$$\mathbf{ENL=IL + DT}$$

IL is a power sum of the frequency dependent ambient background noise level (in dB re $1\mu Pa/Hz^{1/2}$) and the reverberation level due to surface, bottom and volume scattering. Because the system is intended to operate normally in deep water (>500 m) and relatively short ranges (<2 km), the only significant reverberation component is due to surface backscattering. The detection threshold is principally set by the acceptable false alarm rate and the PDF of the interference levels. Processed receive signals in excess of the DT are considered as detected targets. False alarms are defined as detections where no target is present.

Figure AA-4 shows the mean interference levels for various tilt settings measured during the May 2000 system trials. These trials were run in deep waters (depth > 1000m), and therefore bottom

[3] Equation 2 from Au, W.W.L 1996. "Acoustic Reflectivity of a Dolphin", J. Acoust. Soc. Am. 99(6): 3844-3848.
[4] Love, R.H. 1973. "Target Strength of Humpback Whales *Megaptera novaeangliae*" J. Acoust. Soc. Am. 54(5).

reverberation can be neglected (as is the case under design operating conditions). The results shown here are from tests run sequentially over a short time span and with all other settings fixed (i.e., the only expected changes in interference are due to tilt effects).

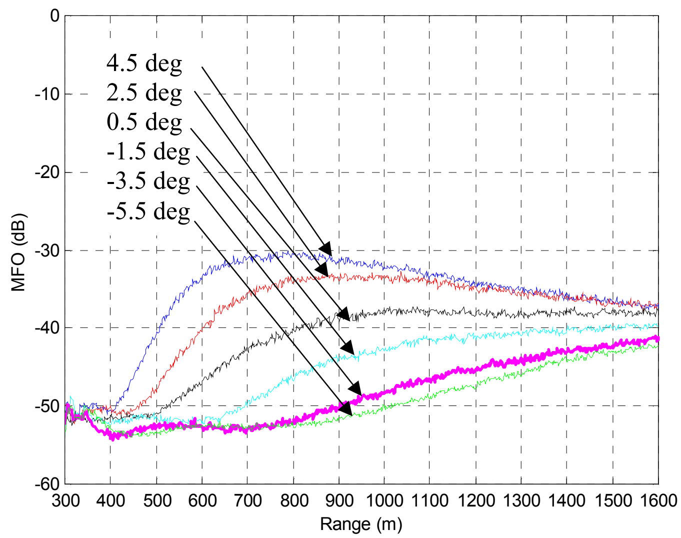


Figure AA-4. Effect of tilt on mean interference level.

Several features of this figure should be emphasized:

- Interference in the 300-400 m region remains unchanged with variations in tilt. Thus, the near range interference is noise dominated. Note that the noise-dominated region extends further as tilt is decreased.
- Beyond 400-800 m (depending on tilt), the mean interference levels are sensitive to tilt setting. In this region, as tilt is decreased the measured interference levels also decrease.
- Predicted surface levels due to mainlobe ensonification display similar range and tilt dependency. Surface backscatter, or surface "clutter", is proportional to surface pressure levels, suggesting that interference beyond 800 m is always dominated by surface clutter. Note that there is no apparent surface reverberation due to sidelobe ensonification.

Based on these observations, we consider surface clutter to be the dominant source of interference for the HF/M3's detection algorithm.

DETECTION ALGORITHM

Several sea trials have been performed with the HF/M3 system. The Hawaii 2000 Trials were held in deep waters that represented normal operating conditions. During the trial, one full day of testing was dedicated to a study of interference and target echo levels. Analysis of the data collected during this trial was used to generate system performance estimates. Table AA-2 summarizes the environmental and system parameters present during testing.

Table AA-2. Summary of test parameters for measured data to be used as basis of target and interference statistical models.

Condition	Values
Sea State	2-3
Sound Velocity Profile	Uniform 1530 m/s in surface layer
Surface Layer Depth	Approximately 150 m
System Depth	70 m
Target Depth	70 m
System Tilt	0,-1.5,-2.8 degrees
Pulse BW	1500,3000,4500,6000 Hz
Pulse-length	10,20,40 msec
Estimated Absorption Coefficient	9 dB/km, 2-way travel
Number of Tracking Runs	20
Number of Pings per Tracking Run	300-400
Number of Pings per Azimuthal Sweep	45

As discussed above, there is a nominal tilt setting for any linearly varying sound velocity profile. The measured data analyzed here were primarily collected with a tilt of –1.5 degrees. The optimal tilt for the sound velocity profile present during testing (which was essentially constant, 1530 m/s, within the 150 m deep surface layer) is estimated to be –3.5 degrees. We therefore anticipate surface clutter interference in these data to be in excess of that normally expected.

Target Model

During testing, a spherical target (TS = –8dB) was deployed from the Research Vessel (R/V) *Cory Chouest*, the staging vessel of the HF/M3 system. The R/V made repeated runs past the target with closest points of passage between 300 and 1500 m. System parameters (such as pulse-length, bandwidth, and projector tilt) were varied in a controlled manner during this testing, allowing for parametric study of both target echo and interference statistics. Results from a typical run are shown in Figure AA-5. Because the target used here is essentially stationary, a track can be visually established and used to discern true from false detections.

Table AA-3 summarizes results from this and numerous other tracking runs. Using the system properties (tilt setting and vertical beampattern) and environmental conditions (i.e., sound velocity profile) present during testing, the transmission loss at the measured target range was computed using the range-independent ray code BELLHOP. The expected echo levels can then be estimated using the methods outlined in the background section. The target depth is assumed to be that of the sonar system (the mooring line from which the target was suspended was as long as the depth of the HF/M3). Changes in depth due to currents will be a source of error in the echo level predictions.

The mean difference between the predicted and measured echo return fluctuates about zero, suggesting that the model of mean target echo level is reasonable. The average standard deviation of all runs is approximately 5 dB. Insufficient samples are available, however, to estimate the form of the target echo PDF. For the present analysis, we will assume the target echo level PDF to be normally distributed.

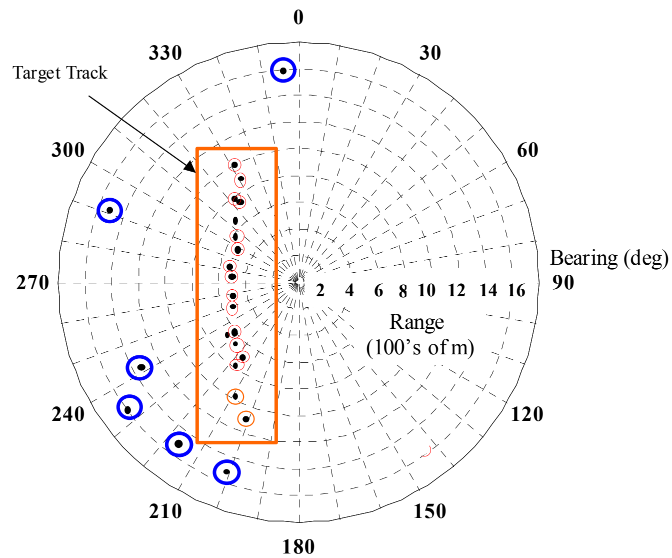


Figure AA-5. Tracking run detections (tilt of –1.3 deg, BW of 4500 Hz, pulse length of 20 msec). Black dots are instances when the threshold level was exceeded. Detections that are circled in red are associated with a stationary deployed target with TS of –8dB. Detections circled in blue are considered false alarms. 6 false alarms, the majority occurring beyond 1400 m, occurred during the 30 azimuthal sweeps shown.

Table AA-3. Summary of Detections for –8dB target

Tracking Run ID	Pulse Bandwidth (Hz)	Pulse Duration (msec)	Tilt* (deg)	Mean Difference Between Predicted Echo Level and Measured Echo Levels** (dB)	Standard Deviation of Difference Between Predicted Echo Levels and Measured Echo Levels (dB)
1	4500	40	-2.8	0.1	5.1
2	4500	40	-2.8	-2.0	2.1
3	4500	40	-1.5	-2.3	4.1
4	4500	40	-1.5	-4.3	2.6
5	3000	40	-1.5	3.4	6.0
6	6000	40	-1.5	-3.7	5.2
7	6000	40	-1.5	7.0	6.8
8	1500	40	-1.5	-1.5	4.3
9	4500	20	-1.5	-1.6	6.2
10	4500	10	-1.5	-0.1	6.2
11	4500	10	-1.5	2.8	6.9
12	4500	40	-1.5	4.9	6.1

* positive upward
** measured - predicted

Interference Model

Figure AA - 6 shows predicted curves of acoustic pressure levels generated by the HF/M3 as a function of range and for several configurations, including that studied here (depth of 70 m, sound-velocity-profile slope of 0.01 s^{-1}, -1.5 degree tilt). The two other curves show the predicted surface pressure with the system at 70 m and the optimal tilt setting for two alternate sound velocity profile cases.

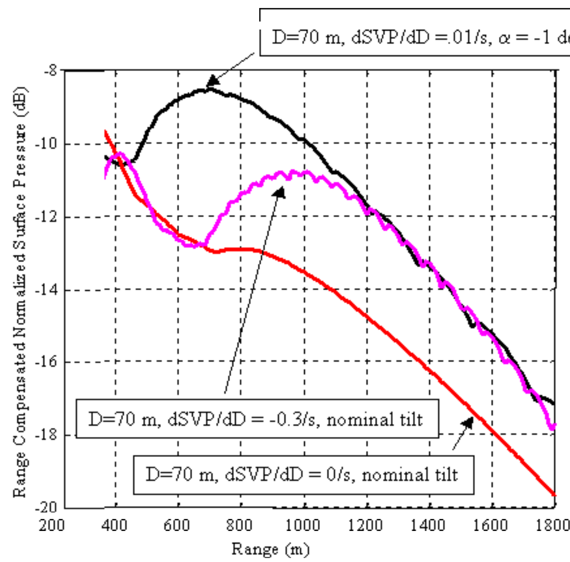


Figure AA - 6 – Predicted normalized surface pressure for various sound velocity and tilt configurations. The highest levels are associated with the configurations studied here. The remaining curves are associated with optimal tilt settings for various sound velocity profile slopes and system depths.

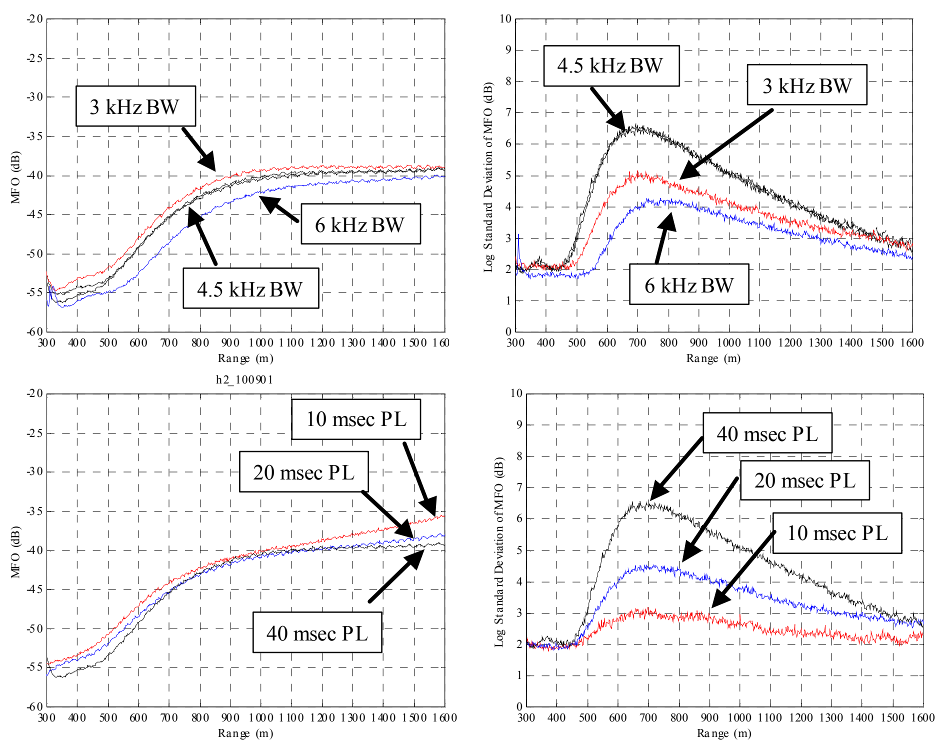


Figure AA-7. Effect of waveform parameters on mean interference level and interference levels standard deviations. The BW variations are performed with a fixed 40 msec pulse length, and the pulse length variations are performed with a fixed 4.5 kHz bandwidth. All cases have a –1.5 degree tilt setting.

The figure illustrates that the as-tested configuration and environmental conditions combine to give higher surface levels (and hence backscatter levels) than would normally be expected. Thus, the surface clutter model is conservative based on the current dataset.

Figure AA-7 shows the effect of pulse bandwidth and duration on measured interference mean and standard deviations.

For a linear chirp waveform, mean surface clutter is expected to be relatively insensitive to pulse length, as is illustrated in the lower left-hand plot. The surface clutter is expected to diminish with increasing bandwidth, as is illustrated in the upper left-hand plot. Changes in the surface clutter variance with variations in pulse-length and bandwidth are not as easily predicted. The upper right hand figure shows the measured interference standard deviation as a function of range and for several pulse bandwidths (all with a pulse length of 40 msec). The lower right hand figure shows the measured interference standard deviation as a function of range and for several different pulse lengths (all with a bandwidth of 4.5 kHz). The mean interference is minimized for the highest pulse bandwidths considered (6 kHz). The standard deviation is smallest for the shortest pulse-lengths of interest (10 msec). However, no data are available for the apparent optimal pulse-length/ bandwidth combination. We choose to base our interference model on the 6 kHz, 40 msec case as it represents the best combination of those with measured data.

The interference is assumed to be normally distributed, and measured data appear to fit this assumption well. However, computations of false alarm rates will be sensitive to this assumption, so measurements will continue to validate this assumption.

Threshold Algorithm

The thresholding scheme is designed to maximize the probability of detection for an acceptable false alarm rate. Figure AA-8 shows the single-range-cell probability of a false alarm for several noise level standard deviations (with normal distributions) as a function of detection threshold. The interference model used here has a standard deviation less than 4 dB for all ranges of interest. To maintain a single-range-cell probability of false alarm of at most 10^{-5}, our detection threshold must be at least 18 dB for all range cells.

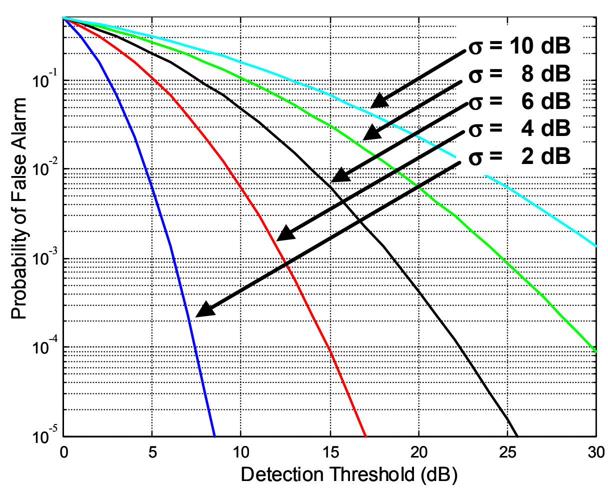


Figure AA-8. Probability of false alarm for several noise level variances as a function of detection threshold. The noise probability distribution function is assumed to be Gaussian.

Figure AA-9 illustrates the detection threshold selected. The left-hand plot shows the mean target echo level (with TS ranging from –12 to 8 dB), the mean interference level and the threshold level. The right-hand plot shows the standard deviation of the interference and target models.

The threshold level used is based on the mean interference level as follows:

$$\mathbf{T = max[EL(R, TSmin) - \Delta_1, - I(R) + \Delta_2]}$$

- T is the threshold level (in dB)
- EL is the expected echo level of the smallest target of interest, (with target strength TSmin, typically –12 dB), at range R
- Δ_1 is an offset to maintain a minimum probability of detection (typically -10dB)
- I(R) is the mean interference level at range R
- Δ_2 is an offset to maintain acceptable maximum false alarm rates (typically 18dB)

Given that the interference statistics can be measured during operation, the free variables TSmin, Δ_1 and Δ_2 can be optimally set in the field.

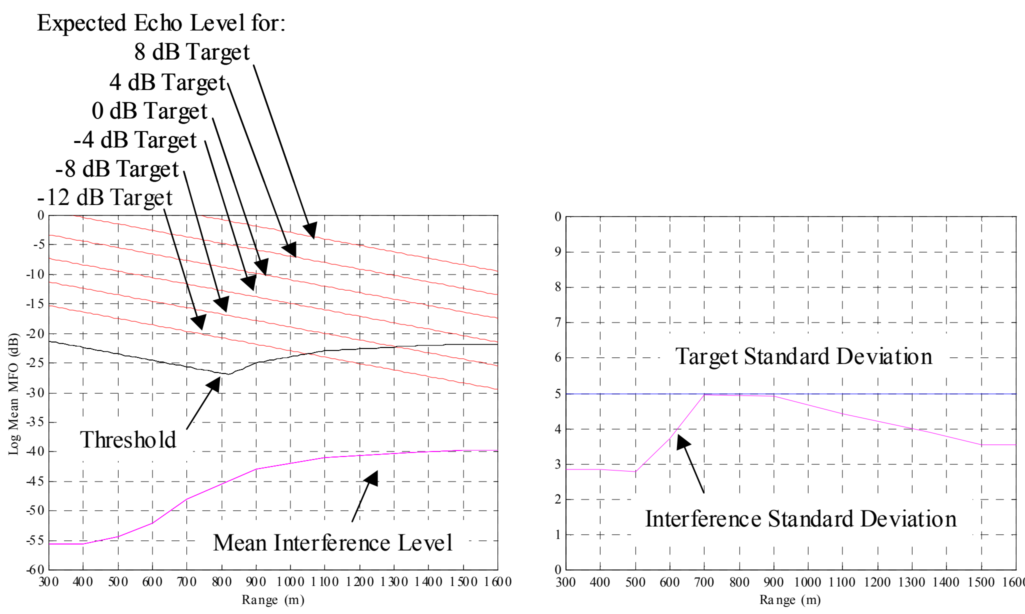


Figure AA-9. HF/M3 thresholding scheme. The left hand figure shows the mean interference, threshold level and predicted mean echo levels for various target strengths. The right hand figure shows the standard deviation of interference and targets. All probability distribution functions are assumed Gaussian.

PERFORMANCE PREDICTIONS UNDER NORMAL OPERATING CONDITIONS

Figure AA-10 shows the probabilities associated with the echo level curves shown in Figure AA-9. As one would expect, as target strength increases so does the probability of detection (PD).

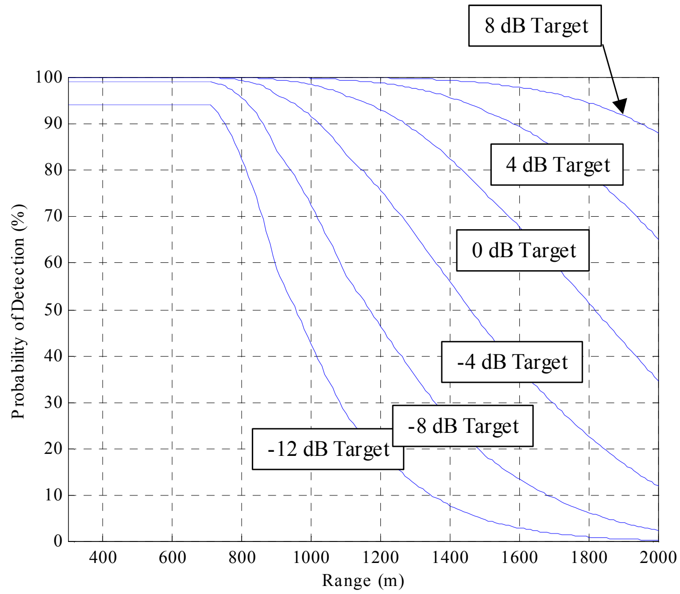


Figure AA-10. Probability of detecting objects of various TS assuming object resides at midpoint of mainlobe (9 dB per km absorption).

Figure AA-11 shows the probability of detecting a –4dB target as a function of depth and range for a neutral refracting environment (uniform sound velocity slope). The PD is nearly one throughout the main sub area of interest in the LFA mitigation zone (white box). At the outer edges of the LFA mitigation zone, the PD decreases to 50 percent and falls below 10 percent beyond approximately 1,250 m.

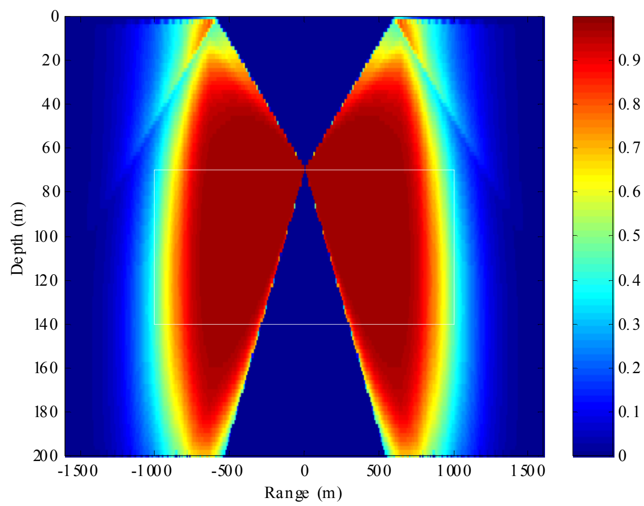


Figure AA-11. Probability of detecting –4dB target at various field points for uniform sound velocity.

The total false alarm rate is the expected number of false alarms per azimuthal sweep, for which 45 range scans are made. The total false alarm rate can be computed from the following equation:

$$FA = 45\sum_{i=1}^{n} P(FA, R_i)$$

Here, n is the number of range bins within the region of interest. In the 200-800 m region, there are 350 range bins and in the 800-1600 m region there are 450 range bins. The false alarm rate in the 200-800 m range is estimated at 1 FA every 350 azimuthal sweeps (with most of the FA's occurring in the 700-800 m range), and in the 800-1600 m region it is about 1 FA every 25 azimuthal sweeps.

CONCLUDING REMARKS

This document presents measured and predicted performance estimates of the HF/M3 active sonar system. A thresholding scheme was derived to minimize the false alarm rate in the 200-800 meter region and maintain a probability of detection in excess of 95 percent for small marine mammals (e.g., pilot whale or beluga). When searches concentrate on larger marine mammals (e.g., humpback whales), the false alarm rates fall below 1 every 1000 azimuthal sweeps.

The system performance is relatively insensitive to environmental factors such as refraction (assuming sound velocity profiles are somewhat linear and not characterized by excessive changes with depth) and sea state.

As mentioned previously, qualitative assessments of the system's ability to detect marine mammals of various sizes have been verified in previous sea trials. In roughly 170 hrs of at sea testing, 6 whales have been spotted on the surface after strong detections were made on the HF/M3 system. A dedicated experiment designed to verify the system's ability to detect bottlenose dolphins provided strong evidence that this is so. Seventy-five other objects have been detected during testing which are believed to be marine mammals.Finally, there are a host of simple techniques yet to be explored which could potentially reduce the false alarm rates predicted here. For example, it is hypothesized that a main contributing factor to high interference standard deviation is the pitch and roll of the HF/M3 system itself. Because pitch and roll sensors are already installed on the system, it would be a simple addition to the system software to reject detections made on channels with momentarily high tilt due to unsteady source motion. Other standard clutter rejection techniques, such as ensemble averaging or M-of-N criteria matching, have yet to be fully explored.