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Scientific Fishery Systems, Inc. (SciFish) has investigated and validated the feasibility of making consistent acoustic measurements of absorption to obtain a temperature. Historically, absorption measurements were made via long baseline, open ocean experiments where absorption was not the primary measured quantity, or via exacting laboratory conditions where absorption was examined for specific chemical, temperature or pressure dependencies. Our goal has been to make a short baseline measurement of absorption in open waters.

In prior work, we have found that a narrowband approach with a high resolution ADC was technically possible but economically infeasible for the scope of the existing effort. As such, an alternative method was devised using analog electronics that could perform the essential dynamic range expansion using the differences between successive range cells. The approach eliminated some of the most serious difficulties in making this measurement. General attributes of the modified system are as follows:

- It is ambient noise limited. Thermal noise constitutes the dominant generation mechanism at these frequencies, added source level should lead directly to added range. Favorable SNRs were achieved up to 30m in range
- It significantly reduces the effect of target strength variation, provided sufficient volume is averaged over the range cell to include a population with the full range of specular returns.
- It obtains a salinity profile at the points of temperature reversal that occur in all of the theoretical absorption vs. frequency curves proposed by the research community.
- It can provide a temperature profile with <1.5% uncertainty (3-13m range, up to 3% at ranges up to 30m) based on measurements made in the harsh (low density, small reflectors) freshwater environment. An error analysis indicates that the best previous data for absorption had an error of ±1.5% that results in a temperature error of ±0.08°C.

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# Final Report
for
# Phase II Small Business Innovation Research Project
# "Automated Broadband Acoustic Sound Velocity Profiler"

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## Executive Summary

Scientific Fishery Systems, Inc. (SciFish) has investigated and validated the feasibility of making consistent acoustic measurements of absorption to obtain a temperature. Historically, absorption measurements were made via long baseline, open ocean experiments where absorption was not the primary measured quantity, or via exacting laboratory conditions where absorption was examined for specific chemical, temperature or pressure dependencies. Our goal has been to make a short baseline measurement of absorption in open waters.

In prior work, we have found that our broadband system is unable to make these measurements because of poor SNR and that a narrowband approach with a high resolution ADC was technically possible but economically infeasible for the scope of the existing effort. As such, an alternative method was devised using analog electronics that could perform the essential dynamic range expansion using the differences between successive range cells. The approach eliminated some of the most serious difficulties in making this measurement.

In this project modifications were made to existing equipment to test the concepts put forth in a previous study that showed, in theory, a temperature profile might be extracted acoustically. Using a new and innovative method of processing the acoustic signals led to:

1. Reducing the number of bits needed in an Analog-to-Digital Converter (ADC) from a minimum 18 to 12, and
2. Reducing various sources of errors in the measurement, primarily knowledge of target strength (potentially a 10 dB error by itself).

A patent on this novel methodology is currently being considered.

In this work we made critical *in-situ* measurements to validate an ability to reduce the ping-to-ping variability in measurements, a point considered essential by Dr. Robert Francois[1], for the general technique to proceed. To provide an honest evaluation of the approach, we delayed testing to await conditions in the field that minimized interfering influences, due to a winter with record setting rain and wind in the Pacific Northwest. The conditions in the salt-water environment have only now reaching the necessary sea-state to conduct reasonably controlled experiments. We accomplished all of the testing that produced acceptable data in fresh-water, spring-fed Lake Crescent on the Olympic Peninsula.

Taking the difference levels in successive, small, range-cells obviates the need for absolute knowledge of source level, target strength of the volume reflectors and ambient noise because they are all subtracted out in the difference process. Additionally, this method avoids a very costly (both in hardware and software) ADC. The output of the new hardware is a direct, highly amplified, measure of the combination of spreading loss and absorption – the slope of the signal change. This means that changing frequencies to regions where absolute absorption is higher will make the measurement easier. The current test platform was designed to find and identify fish, thus it is limited by design and construction to a maximum of 190 KHz. General attributes of the modified system are as follows:

[1] Personal communication, October 13, 1998, co-author of seminal papers in absorption, now retired from University of Washington, Applied Physics Laboratory.

- It is ambient noise limited, i.e. range-limited by the signal to noise ratio (SNR) at any frequency. Given that thermal noise constitutes the dominant generation mechanism at these frequencies, added source level should lead directly to added range. Favorable SNRs were achieved up to 30m in range.
- It provides an output directly proportional to the spreading and absorption signature.
- It significantly reduces the effect of target strength variation, provided sufficient volume is averaged over the range cell to include a population with the full range of specular returns.
- It obtains a salinity profile at the points of temperature reversal that occur in all of the theoretical absorption vs. frequency curves proposed by the research community.
- It can provide a temperature profile with <1.5% uncertainty (3-13m range, up to 3% at ranges up to 30m) based on measurements made in the harsh (low density, small reflectors) freshwater environment. We expect to obtain the same resolution in saltwater, as all of the error is in the absorption term (electronic errors are more than an order of magnitude less). These measurements are at least as good as any made to date (Francois-Garrison, 1982[iii,iv]). An error analysis indicates that the best previous data for absorption had an error of ±1.5% that results in a temperature error of ±0.08°C.

The next generation system will provide temperature profiles with up to 0.8°C accuracy. This will be accomplished by making the following modifications to the existing system:

- Operate at a number of higher frequencies to provide higher absorption values to measure - Increasing frequency increases the absolute absorption, thus the proportion of the signal above the spreading loss (20Log(range)) increases with frequency and the ease of measurement increases with frequency,
- Integrate a –20log(2r) amplifier to remove the spreading loss component and get an output reading directly proportional to absorption,
- Integrate over multiple small range cells to remove variability in the volume target scattering,
- Increase source level and, potentially, to have multiple, overlapping beams to gain reliable ping-to-ping data on rolling platforms,
- Operate in a number of different modes as the range is increased. The mode used in the current experimental setup was optimized for the highly sloped region of the spreading plus absorption loss curve that exists in the first 10 meters of range examined.
- Measure absolute temperature and absolute salinity at the transducer face as a ground truth reference.
- Be a stand-alone system, capable of installation on a naval vessel for further testing.

# 1.0 - Introduction

The purpose of this project was to determine if the experimental error could be reduced to permit an acoustic process for measuring temperature profiles. Historically, absorption measurements were made via long baseline, open-ocean experiments where absorption was not the primary measured quantity, or via exacting laboratory conditions where absorption was examined for specific chemical, temperature or pressure dependencies. Our goal has been to make a short baseline measurement of absorption in open waters. Knowing that the measurement cannot be made broadband (poor signal to noise), or narrowband with existing ADC boards, we opted to investigate an approach that performs several critical functions with new generation high-speed, very low-noise analog electronics available only in the last 6 months.

The chosen approach uses the detection of changes in absorption of acoustic energy throughout the water column. The feasibility of the proposed process was explored mathematically in a previous study[i]. Various academic research reports were reviewed and a mathematical model was developed for the purpose of estimating absorption coefficient over a limited frequency range. The model was used to illustrate the detectable changes, which will occur in the volume reverberation of seawater at various frequencies. This effort concentrated on refining the experimental results to verify the theoretical concepts.

An attempt was made to acquire actual temperature profile information using the detection of absorption coefficient changes. The existing hardware and software system, the Scientific Fishery Systems SciFish 2000 broadband sonar was deployed in Hood Canal, a salt water fjord, and in Lake Crescent, a spring fed mountain lake, for several measurement trials. A conductivity, temperature, and depth (CTD) probe was also deployed for comparative ground truth purposes. The first attempts to acquire acoustic temperature profiles with the existing sonar did not succeed because of system noise limits. This effort reduced that noise, and in fact bypassed many of the errors associated with the standard measurement schemes. This report presents the results of field trials using the modified hardware that resulted in significant improvements in the ability to measure absorption.

## 1.1 - The Problem

Temperature profiling is slow and somewhat expensive. Again historically, obtaining ocean temperature profiles has been routine oceanographic procedure, while ocean currents could only be estimated indirectly from the temperature field or from the motion of drifting sensors. Today the situation is reversed, in that current profiling is easier than temperature profiling, at least within the top few hundred meters. The advent of precise navigation systems and ship-mounted Acoustic Doppler Current Profilers (ADCPs) has allowed continuous remote profiling of currents while underway. In contrast, each temperature profile is relatively costly, either in the time lost in stopping the ship for the duration of a CTD cast or the expense of an XBT (expendable bathythermograph).

Development of a remote temperature-profiling instrument would allow naval, oceanographic and fishing vessels to cover more area more quickly and obtain temperature (T) and salinity (S) to suit their respective needs. The most common applications of temperature profiles actually require either density profiles or sound speed profiles. Examples of each are respective determination of the baroclinic component of the pressure field and compensation of acoustic path for refractive displacement. Both of these examples are applications where the quantity of interest involves integration of a profile over a range of depths. Errors in the measurement of these quantities are therefore more sensitive to profile errors of low spatial frequency vice those of high spatial frequency. The nature of the short-term errors in the proposed acoustic temperature profiling method make it well suited to this type of application, in contrast to applications where small-scale vertical density gradients are of interest.

High-accuracy CTDs are designed for deep ocean applications where density changes in time and space are so small that absolute accuracy on the order of a milli-degree Celsius is required. In the top 300 m of the water column within reach of a ship-mounted 150 KHz sonar, however, density features are much stronger, so that much less accuracy is needed in most applications. In applications such as finding and visualizing thermo-haline features (jets, rings, eddies, river plumes, etc.), the advantage of continuous remote coverage without stopping would generally outweigh the drawback of reduced accuracy.

## 1.2 - The Approach

The SciFish approach to this effort was as follows:

- Modify existing hardware to facilitate acquisition of data to support the concept of acoustic temperature profiling;
- Make field measurements in support of the proposed techniques with a modification of an existing SciFish sonar system; and
- Demonstrate that the measurement technique is capable of rendering more accurate measurements than currently exists via reduced variance of the acquired data.

## 1.3 - The Opportunity

The ability to quickly and accurately determine the temperature profile for a given area is of great significance to several communities. The primary target for this technology is the Naval Defense community. The Navy can use this information to determine acoustic propagation effects of sound transmission as well as investigate transient thermal events. In addition, the ability to determine temperature will allow for the correction of refraction during side scan sonar imaging, hence providing more accurate mine hunting capabilities. The bottom mapping communities will also profit from the same refraction compensation.

As a secondary market, the ability to perform temperature profiling will have an immediate impact in the oceanographic communities and fisheries. The temperature range that fish live within varies with age and species. As such, the ability to determine the temperature profile will provide a mechanism for fishermen to selectively harvest target species and reduce bycatch.[ii]

## 1.4 - Final Report Roadmap

This report is organized into 6 sections. Section 1 briefly discusses the background, approach, and the opportunity. Section 2 reviews the mathematical model. Section 3 provides details of the modifications to the sonar. The SciFish 2000 sonar is reviewed in Section 4. Section 5 discusses the conduct of the field tests and the results. Section 6 discusses the feasibility of the technique to acquire temperature profiles and includes basic system engineering requirements for a next generation acoustic temperature profiler. Section 7 reviews the commercialization plan.

## 2.0 – Theoretical Foundation

Our work follows from the most comprehensive analysis of temperature and absorption collected to date (Francois and Garrison[iii,iv]). This project builds on the work of Francois and Garrison by exploiting the shape of the curve (**Figure 1**) to determine first a salinity profile, then shift frequency to obtain the temperature profile.

The curve of total absorption exhibits several interesting features: two interesting reversals of temperature dependency: one near 70 KHz, the second near 500 KHz, and the logarithmic increase in absorption. There is not a comparable reversal in the Salinity dependency. To highlight the areas of our testing, **Figure 2** illustrates the combination of spreading loss and absorption with different conditions of salinity and frequency (fresh water with 0 ppt salt and saltwater with 30-ppt total salinity). The plots are shown for the test frequency of 153 KHz, and for a potential operating frequency of 500 KHz, for illustration.

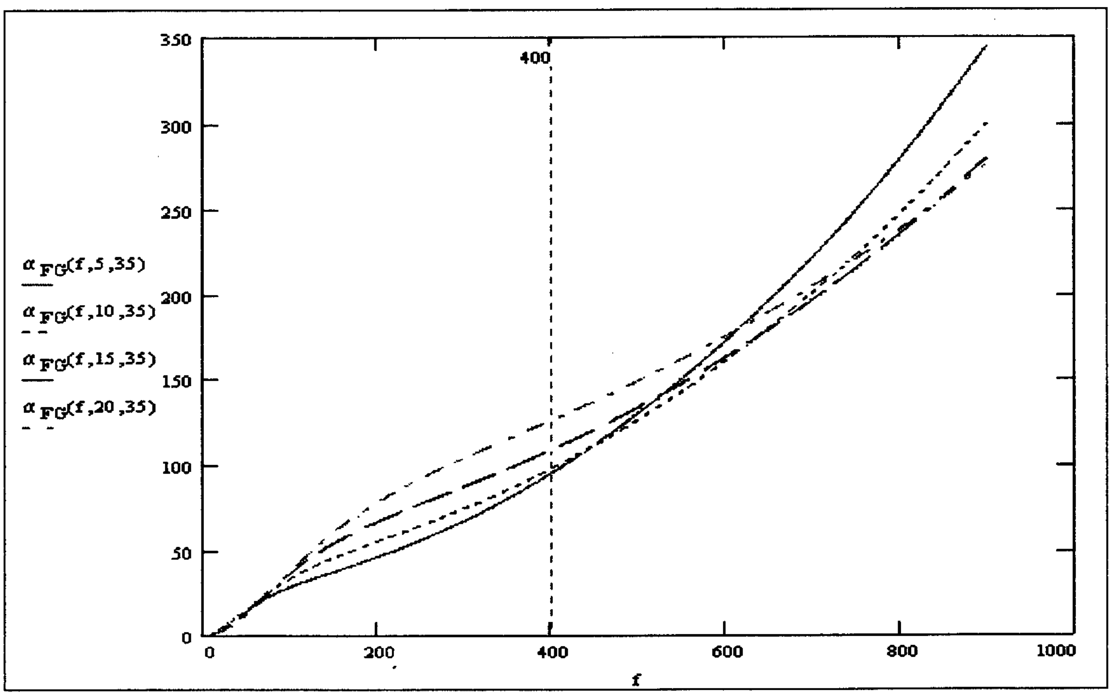


Figure 1. Absorption per Temperature Vs Frequency

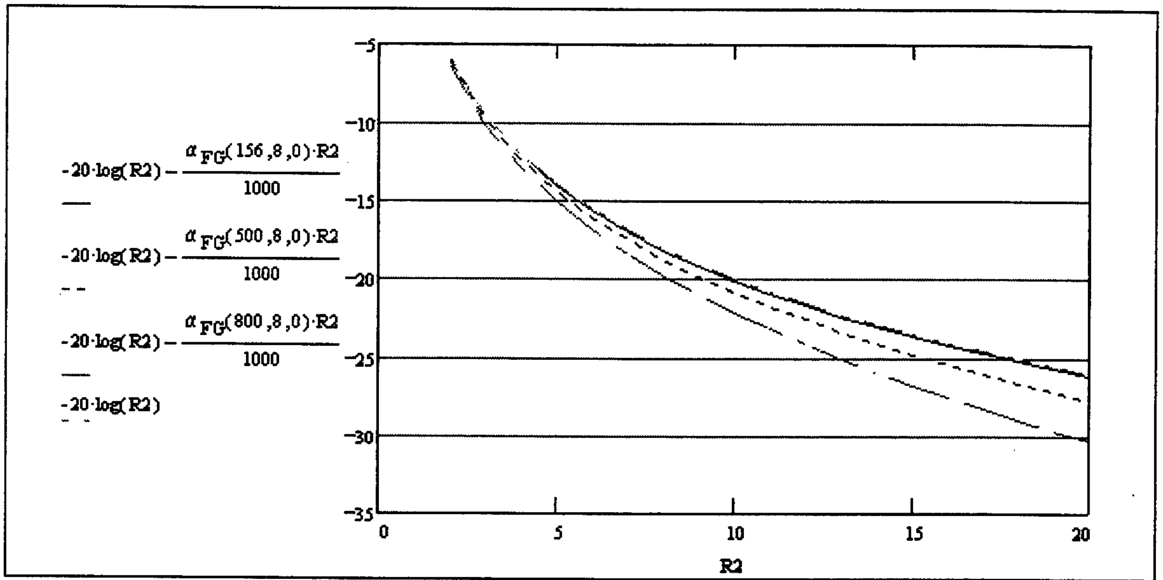


Figure 2. Spreading and Absorption for Freshwater at Several Frequencies

Note that the 4th curve is only spreading loss, and that the difference between spreading only and spreading with absorption in fresh water at our operating frequency is extremely small. If the spreading loss can be removed, the resultant output would that reflected by **Figure 3**, which shows the differing responses due to both frequency and salinity at a constant temperature. This type of display retains the range factor, as a proportionality factor. This last figure (Figure 3) would be the type of display possible with removal of the spreading loss from the current hardware implementation: a direct reading of absorption.

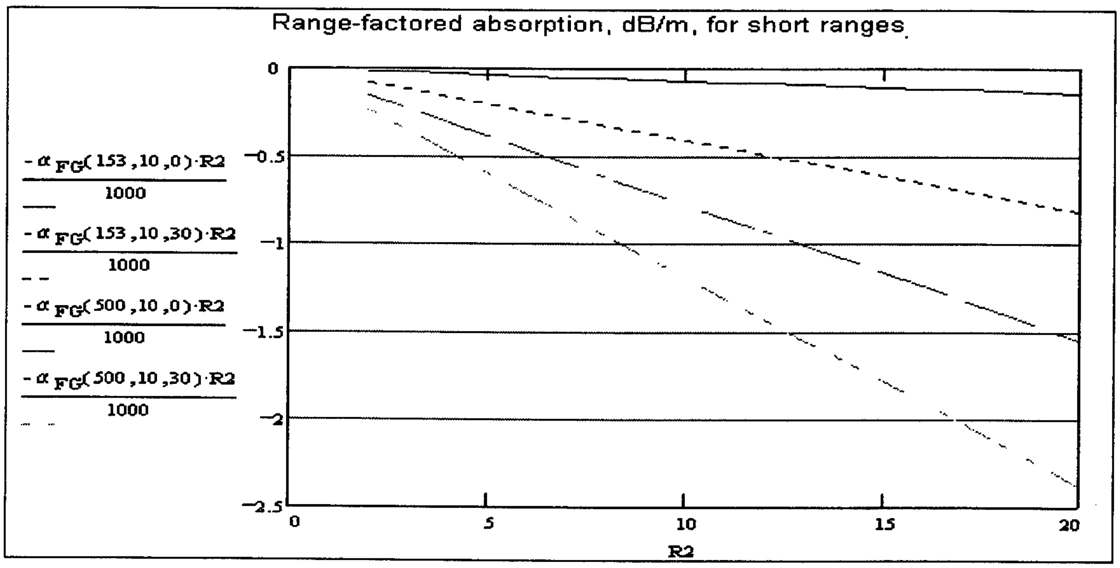


Figure 3. Predicted Absorption Loss Curves for several Frequencies

# 3.0 - Analog Sonar Circuitry Description

The measurement necessary in the Acoustic Temperature Profiler (ATP) project required SciFish to design and fabricate an analog front-end (front-end includes all the receiver pre-amplification, filtering, etc.) and detector. The following pages present a high level description of this custom circuitry. A discussion of detection technique will be highlighted, as this is the novelty of the approach taken to estimate the water temperature by acoustic means.

## 3.1 - Basic Functional Description

The Functional Block Diagram below (Figure 4) is a high level diagram of the custom circuitry. The electronic circuitry to implement these blocks is all housed in one enclosure.

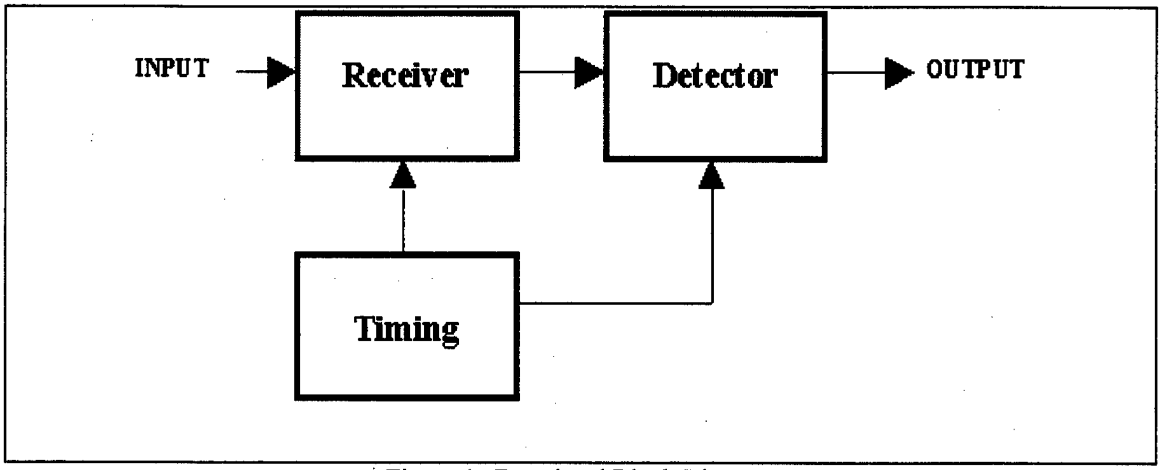


Figure 4. Functional Block Diagram

The input to the system is an acoustic signal representing the reverberant backscatter from a single frequency ping projected into the water. The receiver, under control of the timing, conditions low-level AC analog signals. The detector, also under control of the timing, provides a DC voltage output. The following subsections dissect the circuitry into finer functional blocks.

## 3.2 - Receiver Circuitry

The purpose of the receiver circuitry is acquisition of the acoustic energy of the volume reverberation resulting from the transmitted sonar pulse. Electrical analog signal conditioning in this circuitry amplifies desired signals and filters to reject unwanted noise. The resultant, high level conditioned signal is routed to a detector stage.

The receiver circuitry **(Figure 5)** consists of four functional blocks as follows:

- Hydrophone and Preamplifier
- Adjustable Gain Filter Amplifier
- Bessel Bandpass Filter
- Post Filter Amplifier

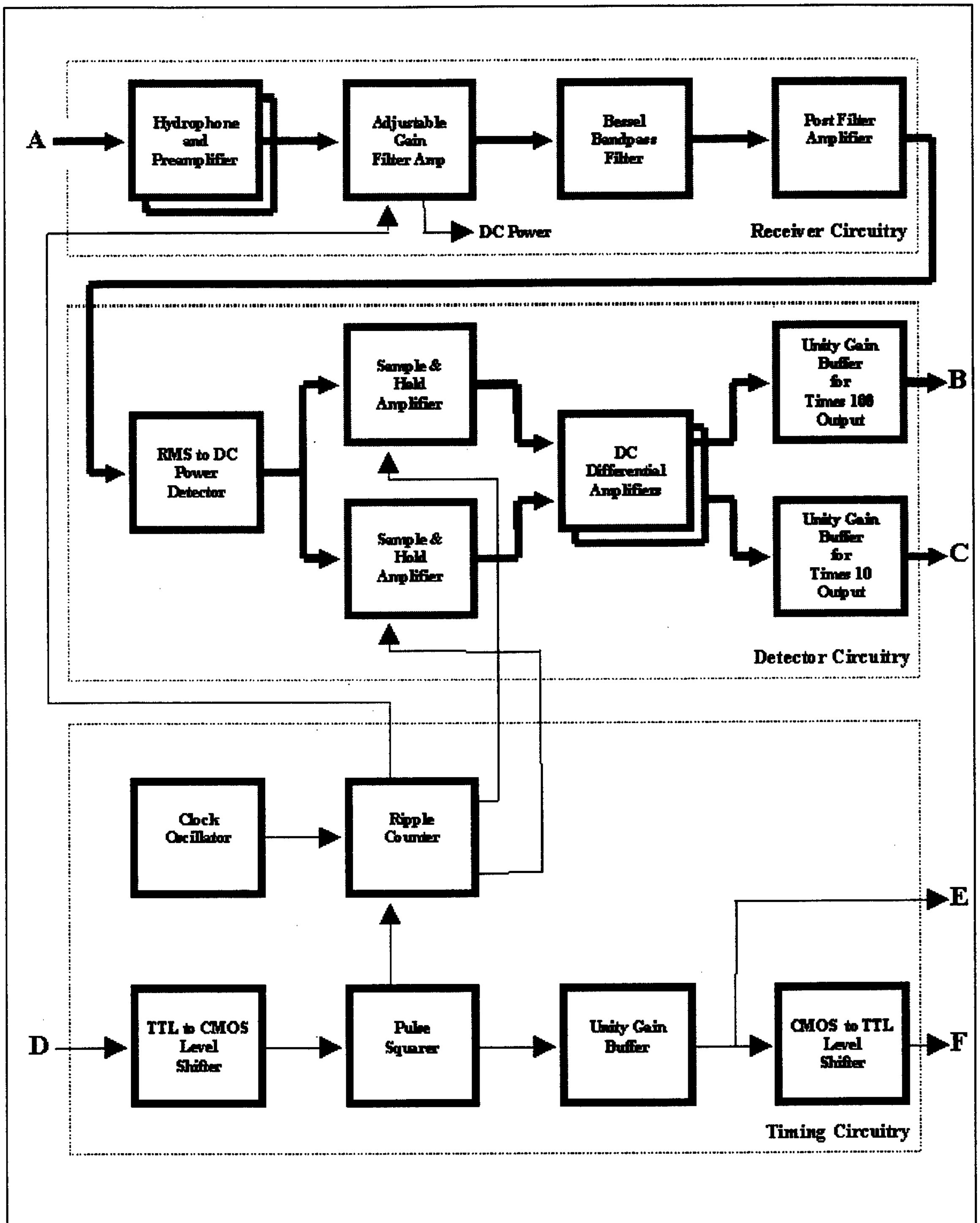


Figure 5. Analog Sonar Receiver, Detector, and Timing Block Diagram

3.2.1 - Hydrophone and Preamplifier

The ATP Project used two independent hydrophones and preamplifiers during the experiments.. We set out initially to use a second hydrophone, with a preamplifier integral to the encapsulated sensor. This hydrophone was totally independent of the transmitter section of the sonar suite to minimize the effects of ringing by the drive signal onto the projector. The backup receiving element utilized the SciFish 2000 transducer as both a hydrophone and projector. This unit contains a selectable gain preamplifier integral to the sonar enclosure that provided a number of fixed steps of voltage amplification.

The independent hydrophone and preamplifier used during the initial experiments was a totally encapsulated, polyvinylydine fluoride (PVDF) sensor with an integral 34 dB gain preamplifier, all permanently potted to a 30 meter cable. The hydrophone exhibits a sensitivity of -154 dB re: 1 Vrms per micro Pascal and is flat to approximately 300 KHz. The sensor develops a narrow beam pattern as the frequency increases. At spectral regions examined during the experiments, a conical bow tie pattern of 15 degrees was fully developed. The experimental setup had the PVDF hydrophone mounted on a Lucite arm that was, in turn, glued to a PVC pipe section. Acoustically absorptive backing material was placed in between the hydrophone and the Lucite to eliminate the back lobe of the beam pattern. An aluminum alignment jig steered the single 15 degree beam parallel to the transmit projector beam.

The use of an independent hydrophone was originally specified because SciFish felt that a bistatic sonar configuration would be advantageous in the elimination of some noise problems observed in earlier testing with the sonar, as well as the desire to place the receiver further down in depth. Another perceived advantage was sensitivity. The PVDF hydrophone, with its response flat to 300 KHz, would allow the use of any frequency that could be projected by the transmitter. The results of the experiments, however, showed that the difficulty of aligning the PVDF hydrophone with the very narrow, four degree transmit projector beam was more of a problem than the ringing of the projector. This was made more difficult by maintaining that critical alignment during tests in the less than perfect weather conditions that plagued the winter experiments and did not outweigh the simplicity of using the inherently aligned projector and hydrophone combination available with the SciFish 2000 sonar. The noise problems referred to above were located and mitigated.

The second hydrophone (SciFish 2000) and preamplifier used for the experiments, the one which provided the best of the data collected, uses the transmit projector for the acoustic sensor and connects to a stepped gain preamplifier within the sonar enclosure. The hydrophone exhibits a mid band sensitivity of -180 dB re: 1 Vrms per micro Pascal and is operational over a 120 KHz band centered at 156 KHz. A series of four, 20 dB gain amplification steps are available by command from a lunch box computer which operates the SciFish 2000 sonar. The projector and hydrophone develop 4° conical beam patterns in one direction. There is not an alignment issue using this configuration.

It was discovered, during the later experiments, that the rapid mechanical excursions experienced by the sonar head during inclement weather aboard the small 16 foot vessel steered the receive beam away from the ensonified volume backscatter enough to invalidate some of the earliest collections of data. Stabilization of the array combined with nicer weather conditions substantially improved the results. During Phase II, marine experiments will be conducted aboard a large stable vessel, hence mitigating this problem in the future.

3.2.2 - Adjustable Gain Filter Amplifier

The full bandwidth, preamplified signals from the hydrophone used at the time were connected to a laboratory instrumentation filter amplifier for additional gain if necessary, and high pass filtering for rejection of seastate and shipping noise. The instrumentation amplifier used for this purpose in all the experiments was a Low Noise Preamplifier. Gain may be chosen from 1 to 50,000 in a 1,2,5 sequence. (0 dB, 6 dB, 14 dB, 20 dB, 26 dB, 34 dB, 40 dB, etc. sequence to a maximum of 94 dB) The Low Noise Preamplifier also applies various filter functions. For the duration of the experiments, the filter was set as a 12 dB per octave Butterworth high pass filter with the 3-dB point set to a value of 10 KHz. The amplifier was exclusively used with fully differential inputs.

3.2.3 - Bessel Bandpass Filter

Output from the Low Noise Preamplifier instrumentation filter amplifier was connected to a custom designed and fabricated analog receiver, the ATP Processor. The first stage in this circuitry was a band pass filter designed to reject all signal content not within the operational frequency range of the SciFish 2000 sonar transmitter. The filter was specified to have a center frequency of 156 KHz and exhibit a steep, 24 dB per octave roll off with the 3-dB points at about 90 KHz and 220 KHz.

The choice of filter topology was driven by the assumption that the most deleterious in-band noise likely be encountered would be the target backscatter from small fishes or crustaceans within the ensonified water volume. Since the backscatter from these creatures would appear as sharply delineated pulses of higher volume, it was decided that the filter function chosen should do a reasonable job of passing pulse information without smearing the pulse into an adjacent range cell. The Bessel topology for voltage controlled voltage source (VCVS), filters is the wise choice for this type of application. The filter designed for the ATP Processor was fabricated using four stages of VCVS filtering. The first pair were high pass sections, the second pair low pass sections. These stages were realized with operational amplifiers. These are FET front-end, bipolar transistor amplification stage integrated circuits which a re ideally suited to this type of application. The four stage VCVS filter exhibits a mid-band gain slightly more than 6 dB.

3.2.4 - Post Filter Amplifier

The highly filtered output of the Bessel bandpass filter stage was followed by a linear broadband gain stage with a low impedance output. The gain of the stage was set to 20 dB. This stage was also realized with the same operational amplifiers.

The Bessel Bandpass Filter stage and the Post Filter Amplifier stage are the only AC gain stages in the ATP Processor. The transfer function of these stages are shown over a frequency range of 50 KHz to 200 KHz in the plot below (**Figure 6**).

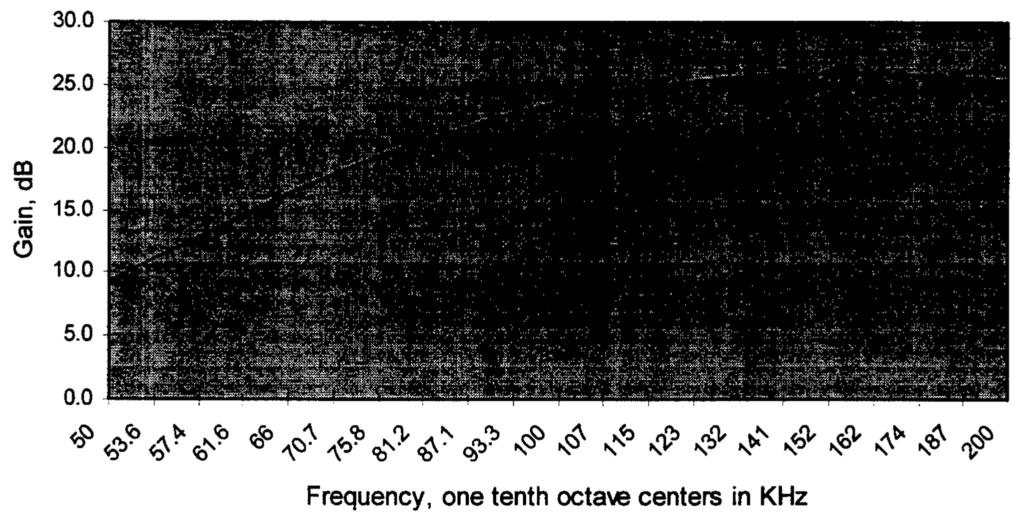


Figure 6. Bessel Bandpass Filter and Post Filter Gain

### 3.3 - Detector Circuitry

The purpose of the detector circuitry (Figure 5) is conversion of the electrical analog AC signal from the receiver circuitry into an analog DC Voltage that represents the energy of the reverberant backscatter. The success of the experiments done in support of the ATP Project largely resulted from this detector circuitry and its novel approach of providing difference signals from range cell to range cell.

The detector circuitry consists of four functional blocks as follows:

- RMS to DC Power Detector
- Sample and Hold Amplifiers
- DC Differential Amplifiers
- Unity Gain Buffers

3.3.1 - RMS to DC Power Detector

In its simplest form, detection of an AC signal may be done with a diode. The result is a DC signal. Using a capacitor and a resistor as a low pass filter provides a smoothed signal. The smoothed waveform will follow the maximum instantaneous value of the input AC waveform. This is the classical Peak Detector. When used in an obstacle avoidance sonar system, this type of signal detection acquires the smallest of targets by following the tiniest variations of the echo backscatter. For the purposes of the ATP, however, this degree of sensitivity to small target information hides the continuum of volume backscatter under a collection of spikes and glitches.

The design goal for the ATP detector was to come up with a circuit methodology that responds to the overall energy of the volume backscatter while effectively ignoring spikes. It is for this reason that the RMS detector was chosen. RMS, the square root of the averaged mean value of the square of the instantaneous input AC signal, is an analog for the absolute power of a particular real waveform. The power within a sharp spike or glitch is very small compared to a continuous function like volume backscatter in relatively clean water. It was hoped that this type of detection methodology would allow measurement of the volume backscatter with a moderate amount of biological backscatter from small crustaceans and similar biota suspended in the beam. Our predecessors in the field of absorption science attempted to use the same type of detection techniques, however, they did not have the precision now available in DC electronic circuits and so could not succeed.

The heart of the ATP RMS Detector is a high speed, 4-quadrant multiplier integrated circuit. The multiplier chosen allows implicit control of a denominator function as well as the more commonly available multiplication of two numerators. With the addition of a few passive components and two integrated circuit amplifiers, a wideband AC RMS to DC converter can be constructed for operation over a nearly 10 MHz bandwidth. The result is a detector that provides a DC output signal that is an analog of the input real power, and it works at the acoustic frequencies where absorption is a significant portion of the overall transmission loss.

The RMS to DC Power Detector designed and built for the ATP Processor was realized with the multiplier and two operational amplifiers. The transfer function of the RMS to DC Power Detector referred to the input of the Bessel Bandpass Filter as shown in **Figure 7**.

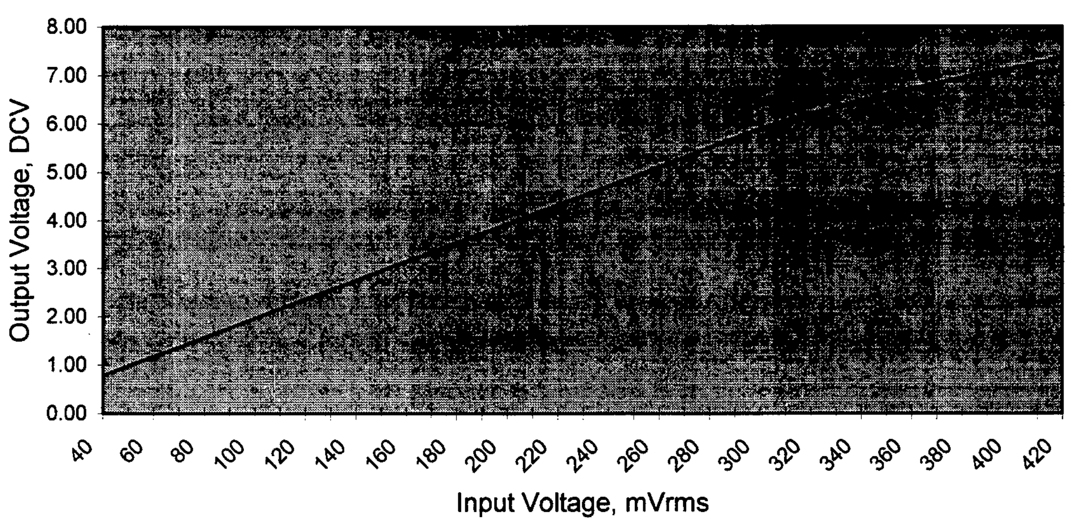


Figure 7. RMS to DC Power Detector Response

The plot shown above shows the DC output of the Power Detector stage in response to an AC input to the Bessel Bandpass Filter stage. A reproducible output can be obtained over a dynamic range of better than 20 dB, however, the truly linear range is somewhat less, approximately 16 dB. Dynamic range figures such as this promise an effective range of about 30 meters for the detector. This was, in fact, the range of the most repeatable data in our field experiments.

3.3.2 - Sample and Hold Amplifiers

The purpose of the Sample and Hold (SAH) amplifiers and the associated timing circuitry is to acquire DC voltage samples from the RMS to DC Detector at a rate which corresponds to the desired sonar range cell distance. The reason for two sample and hold amplifiers will be explained a bit later. The SAH output follows it's input, the DC from the detector, continuously replicating the signal as long as the control voltage from the timing circuitry is in the sample mode. When the control voltage switches to the hold mode, the DC value present at the SAH input is stored as an analog voltage on a very low leakage Teflon capacitor and field effect transistor circuit. This value replaces the continuously varying output until the control voltage once again switches to the sample mode.

The information available now is a series of DC voltage levels that correspond to a piecewise linear representation of the sonar reverberant backscatter. This sampled back scatter signal, in the absence of any unwanted biological target content, represents a voltage analog of the transmission loss, $20 \log_{10} 2R + \alpha 2R$, as a series of DC voltage levels. The aim of the ATP experiments is to devise a methodology that can extract the $\alpha 2R$ component and then process this for $\alpha$ to estimate the water temperature.

A simplification of the methodology selected for measuring $\alpha$ and estimating the temperature values is as follows:

- A temperature value at the face of the transducer would be obtained by direct measurement.
- Temperature would be used to establish alpha at the face of the transducer.
- A sample of the reverberant backscatter level would be taken at a distance R from the transducer.
- The distance would be used to establish the $20 \log_{10} 2R$ transmission loss.
- The $20 \log_{10} 2R$ component would be compared with the measured transmission loss to establish the difference.
- This calculated difference would be processed as the $\alpha 2R$ component.
- The processed alpha value would be used to estimate temperature at the distance R from the transducer face.

This process would continue by utilizing the calculated value of $\alpha$ in each range cell as the reference for the estimate in the next range cell. A series of differential values would be needed to obtain the cell to cell $20 \log_{10} 2R$ value differences. This is where the second SAH comes into the picture. The timing of the hold control voltages for the two SAH amplifiers is designed so that a valid time exists in which the held voltages for two adjacent cells are present at the same time. These two voltages may be subtracted so as to directly measure the difference, the $(20 \log_{10} 2R_1 + \alpha 2R_1) - (20 \log_{10} 2R_2 + \alpha 2R_2)$, between cells.

The SAH Amplifier circuitry designed and built for the ATP Processor was realized with monolithic SAH integrated circuits. These SAH amplifiers allow the designer to implement any size of storage capacitor desired so that long hold times, a consideration for the temperature profiler application may be established.

3.3.3 - DC Differential Amplifiers

The DC Differential Amplifier stage is the one designed to provide the subtraction necessary for the $(20 \log_{10} 2R_1 + \alpha 2R_1) - (20 \log_{10} 2R_2 + \alpha 2R_2)$ difference from cell to cell. The DC voltages held by the SAH hold stages are presented to the plus and minus inputs of the differential amplifier, and the difference is produced as the amplifier output. It becomes evident that small cell range differences will mean small $(20 \log_{10} 2R_1 + \alpha 2R_1) - (20 \log_{10} 2R_2 + \alpha 2R_2)$ differences. To take advantage of this situation, the differential amplifier stage is designed so that the output is not just the difference voltage; it is the difference voltage multiplied by a precise value. This multiplication of the difference result, of course, magnifies the quantity we wish to extract, allowing digitization of the value with a conversion device with a lower and more practically realizable bit size.

The DC Differential Amplifier stage is implemented with two differential amplifiers running in parallel. This was primarily done for the practical aspect of the experiments. One of the differential amplifiers is set to multiply the resultant difference by 10 and the other by 100. As it turned out, the times 100 amplifier was the one used for the signal acquisition system. The times 10 circuit was used as a quality control monitor and was viewed on an oscilloscope.

The DC Differential Amplifier circuitry designed and built for the ATP Processor was realized with low power integrated circuit DC Instrumentation Amplifiers. These kinds of precision DC circuits are responsible for the chance to retry the experiments necessary to estimate temperature in the water by acoustic means. Our predecessors in the field did not have this luxury some 15 or 20 years ago.

3.3.4 - Unity Gain Buffer Amplifiers

The Unity Gain Buffer Amplifier stage is present to provide an electrically low impedance output from the ATP Processor. There are two such stages, one for each of the DC differential amplifier outputs. The Unity Gain Buffer Amplifier circuitry designed and built for the ATP Processor was realized with Operational Amplifiers.

## 3.4 - Timing and System Power Circuitry

The purpose of the Timing and System Power Circuitry is provision of the necessary electronic clock functions and electrical power supply voltages for the proper operation of the analog circuitry.

The Timing and System Power Circuitry (**Figure 5**) consists of six functional blocks which perform three major tasks as follows:

- Logic Clock Functions
- Pulse Squarer Functions
- System Power Functions

3.4.1 - Logic Clock Functions

All of the logic circuitry within the ATP Processor is implemented with CMOS combinational logic components. An independent clock oscillator is used to drive a synchronously resetable counter. Combinational logic is used to establish the various clock signals for control of the sonar receiver. Control outputs include the sample and hold signals, the receiver blank timing and some internal timing levels.

3.4.2 - Pulse Squarer Functions

The SciFish 2000 sonar system, the lunch box portable computer and the Low Noise Preamplifier instrumentation amplifier all require TTL logic for their external timing signals. In addition, the SciFish 2000 sonar TTL transmit trigger is required to synchronize the signal acquisition process with the transmission of a sonar ping. The four functional blocks labeled TTL to CMOS Level Shifter, Pulse Squarer, Unity Gain Buffer and CMOS to TTL Level Shifter perform these functions. All are located within the ATP Processor.

3.4.3 - System Power Functions

The Stanford Research Systems Low Noise Preamplifier instrumentation amplifier also provides a rear panel connection that allows external circuitry to be powered by the battery within the Low Noise Preamplifier. The black box was powered in this manner for all of the Temperature Profiler experiments. During those times it was used, the Cetacean Research Systems PVDF hydrophone hydrophone preamplifier was also powered in this manner.

## 3.5 - Electronic Circuit Error Estimate

The four types of linear integrated circuits used to fabricate the ATP Processor, with their respective specifications for tolerance errors are as follows:

| | |
|---|---|
| **Operational Amplifiers:** | |
| DC Offset error: | 500 μV typical |
| Offset TEMPCO: | 15 μV per $^{O}$C from 25 $^{O}$C |
| Gain error: | 0.03 % |
| **DC Differential Instrumentation Amplifiers:** | |
| DC Offset error: | 25 μV typical |
| Offset TEMPCO: | 0.02 μV per $^{O}$C from 25 $^{O}$C |
| Power Supply Tolerance: | 1 μV per Volt |
| Gain error: | 0.03 % |
| Gain TEMPCO: | ± 1 PPM per $^{O}$C |

| **Sample and Hold Amplifier** | |
|---|---|
| Gain error: | ± 0.004 % |
| DC Offset: | ± 2 mV DC |
| Power Supply Tolerance: | 25 µV per Volt |
| Input Gain Drift: | 3 PPM per $^{O}$C |
| Input Offset Drift: | 15 µV per $^{O}$C |
| **Four Quadrant Multiplier** | |
| Static error: | 0.4 % |
| TEMPCO | 0.004 % per $^{O}$C |
| Power Supply Tolerance: | 0.01 % per $^{O}$C |
| Gain error: | 1 % |

Error estimates have been made for the ATP Processor electronic components from the Bessel Filters to the Unity Gain Buffers. Each stage has been separately estimated.

3.5.1 - Bessel Bandpass Filter Stage

The Bessel Bandpass Filter is an ac-coupled stage not sensitive to the DC offset and DC Temperature Coefficient (TEMPCO) specifications of the active components.

The passive components used for gain setting are 1% precision resistors with 100 part per million TEMPCO. Four components are used to determine the ac gain of each amplifier. With a temperature range of 20 degrees C, the gain uncertainty due to the resistor values is:

$$(4 \text{ X } 4 \text{ X } 0.00001^2)^{1/2} = 0.00004 \text{ or } 400 \text{ PPM} / {}^{O}\text{C, over } 20^{O}\text{C} = 0.08\%$$

The active components used for voltage gain are OPA 2132 integrated circuit amplifiers with gain errors of 0.03%. Four amplifiers are used in the filter section. The uncertainty due to gain errors is:

$$(4 \text{ X } 0.0003^2)^{1/2} - 1 = 0.0006 = 0.06\%$$

The total gain uncertainty is estimated as the square root of the sum of the squares of the passive and active component errors:

$$(0.00002^2 + 0.0006^2)^{1/2} = 0.0006 = 0.06\%$$

3.5.2 - Post Filter Amplifier Stage

The Post Filter Amplifier is an ac-coupled stage not sensitive to the DC offset and DC TEMPCO specifications of the active components.

The passive components used for gain setting are 1% precision resistors with 100 part per million TEMPCO. Two components are used to determine the ac gain of the amplifier. With a temperature range of 20 degrees C, the gain uncertainty due to the resistor values is:

$$(2 \text{ X } 0.00001^2)^{1/2} = 0.000014 \text{ or } 140 \text{ PPM} / {}^{\circ}\text{C, over } 20^{\circ}\text{C} = 0.028\%$$

The active component used for voltage gain is one OPA 2132 integrated circuit amplifiers with gain errors of 0.03%. The uncertainty due to gain errors is:

$$(1 \text{ X } 0.0003^2)^{1/2} = 0.0003 = 0.03\%$$

The total gain uncertainty is estimated as the square root of the sum of the squares of the passive and active component errors:

$$(0.000014^2 + 0.0003^2)^{1/2} = 0.0003 = 0.03\%$$

3.5.3 - RMS to DC Power Detector

The RMS to DC Power Detector is a precision DC coupled circuit that contains three active devices. The circuit does not have any passive electrical components in gain setting circuit locations. The four-quadrant multiplier is self-contained, and the two amplifiers are used in a non inverting voltage follower configuration requiring no feedback resistors.

The active devices used for voltage follower applications are integrated circuit amplifiers with gain errors of 0.03%. The uncertainty due to gain errors is:

$$(2 \text{ X } 0.0003^2)^{1/2} = 0.00042 = 0.042\%$$

The DC offset errors for the integrated circuit amplifiers are 500 μV typical offset with a 15 μV per $^{\circ}$C TEMPCO. Over the temperature range of 5$^{\circ}$C to 25$^{\circ}$C, the offset errors would be typically at a value of 800 μV. The full-scale output of the unity gain buffers is seven Volts DC, therefore the 800 μV offset would be an error of 0.011%. The output uncertainty due to the use of two such amplifiers is as follows:

$$(2 \text{ X } 0.00011^2)^{1/2} = 0.00016 = 0.016\%$$

The active device used for the required signal voltage multiplication and square root function is an integrated circuit four quadrant multiplier with gain errors of 1% if not supplied with DC offset adjustment. The circuitry in the ATP Processor is fitted with DC offset adjustment which allows the overall DC gain to be adjusted to + or - 5 mV about zero for linear gain to an output of five Volts DC. This reduces the gain error to 0.1 %. Uncertainty due to gain errors:

$$(1 \text{ X } 0.001^2)^{1/2} = 0.001 = 0.1\%$$

The DC offset errors, called the static error, for the integrated circuit four quadrant multiplier is 0.4 % with a 0.004 % per $^{\circ}$C TEMPCO. The nature of the circuitry following this integrated circuit is such that the static error will be eliminated leaving only the TEMPCO error. Over the temperature range of 5$^{\circ}$C to 25$^{\circ}$C, the offset errors would be typically at a value of 0.016 %. Uncertainty due to static errors is:

$$(0.00016^2)^{1/2} = 0.00016 = 0.016\%$$

The total gain uncertainty is estimated as the square root of the sum of the squares of the passive and active component errors:

$$(0.00042^2 + 0.00016^2 + 0.001^2 + 0.00016^2)^{1/2} = 0.001 = 0.1\%$$

3.5.4 - Sample and Hold Amplifiers

The Sample and Hold Amplifier is a precision DC coupled circuit. The circuit does not have any passive electrical components in gain setting circuit locations.

The DC offset errors for the integrated circuit sample and hold amplifiers are 2 mV typical offset, with a 15 μV per $^{O}$C TEMPCO. The nature of the circuitry following this integrated circuit is such that the static error will be eliminated leaving only the TEMPCO error. Over the temperature range of 5$^{O}$C to 25$^{O}$C, the offset errors would be typically at a value of 300 μV. The full scale output of the unity gain buffers is seven Volts DC, therefore 300 μV of offset would be an error of 0.004%. The output uncertainty due to the use of two such amplifiers is:

$$(2 \text{ X } 0.00004^2)^{1/2} = 0.000057 = 0.0057\%$$

The amplifiers internally employed for unity gain follower application have an input gain drift of 3 PPM / $^{O}$C and an offset drift of 15 μV per $^{O}$C. Over the temperature range of 5$^{O}$C to 25$^{O}$C, the gain and offset errors would be typically at a value of 360 PPM. The output uncertainty due to the use of four amplifiers, two in each, is as follows:

$$(4 \text{ X } 0.00036^2)^{1/2} = 0.00072 = 0.072\%$$

The total gain uncertainty is estimated as the square root of the sum of the squares of the passive and active component errors:

$$(0.000057^2 + 0.00072^2)^{1/2} = 0.00072 = 0.072\%$$

3.5.5 - DC Differential Amplifiers

The DC Differential Amplifier is a precision DC coupled integrated circuit that contains three active devices monolithically connected and specified with a combined error specification. The circuit does not have any passive electrical components in gain setting circuit locations.

The DC offset errors for the integrated circuit amplifiers are 25 μV typical offset with a 0.2 μV per $^{O}$C TEMPCO. Over the range of 5$^{O}$C to 25$^{O}$C, the offset errors would be typically at a value of 29 μV. The full scale output of the differential amplifiers is seven Volts DC, therefore the 29 μV offset would be an error of 0.0004%. The output uncertainty due to the use of this amplifier is:

$$(2 \text{ X } 0.000004^2)^{1/2} = 0.000004 = 0.0004\%$$

The DC gain error for the integrated circuit amplifier is 0.03 % with a 2 PPM per $^{O}$C TEMPCO. Over the range of 5$^{O}$C to 25$^{O}$C, the gain error would be typically at a value of 0.034 %. The output uncertainty due to the use of this amplifier is as follows:

$$(1 \text{ X } 0.00034^2)^{1/2} = 0.00034 = 0.034\%$$

3.5.6 - Unity Gain Buffer Output Amplifiers

The active devices used for Unity Gain Buffer Output Amplifier voltage follower applications are integrated circuit amplifiers with gain errors of 0.03%. The uncertainty due to gain errors is:

$$(2 \text{ X } 0.0003^2)^{1/2} = 0.00042 = 0.042\%$$

The DC offset errors for the integrated circuit amplifiers are 500 μV typical offset with a 15 μV per $^{O}$C TEMPCO. Over the temperature range of 5$^{O}$C to 25$^{O}$C, the offset errors would be typically at a value of 800 μV. The full scale output of the unity gain buffers is seven Volts DC, therefore the 800 μV offset would be an error of 0.011%. The output uncertainty due to the use of two such amplifiers is:

$$(2 \text{ X } 0.00011^2)^{1/2} = 0.00016 = 0.016\%$$

3.5.7 - Total Analog System Error

The output uncertainty due to the use of all the integrated circuitry and passive components in the signal path is:

$$(0.0006^2 + 0.0003^2 + 0.001^2 + 0.00072^2 + 0.00034^2 + 0.00016^2)^{1/2} = 0.0015 = 0.15\%$$

A gain uncertainty error of ±0.15% corresponds to a ±0.013 dB error (e.g. a gain factor of up to 1.0015 vs. an expected 1.00000, or error (in dB) = 20Log(gain ratio)).

## 4.0 - Test System Description

The field experiments in support of the ATP Project were performed in Hood Canal, a salt-water fjord connected to Admiralty Inlet in Puget Sound, Washington, and in Crescent Lake, a spring fed mountain lake on the Olympic Peninsula in Washington. The tests were staged aboard a trailerable 16' motorboat.

The equipment suite consisted of a modified SciFish 2000 broadband sonar system, an Applied Measurements Systems water quality probe and a PC. Power was supplied with a gasoline driven AC generator.

Several trips were made to the Hood Canal site for tests with the water quality probe alone. Two more trips were made to Hood Canal with the entire equipment suite. The unusually rainy and warm winter, a result of the dominant El Niño condition, caused an excessive amount of river runoff in Hood Canal. A very dirty, low salinity surface layer and a large silt and detritus content caused the researchers to move to a cleaner body of water for the tests.

Crescent Lake, a pristine spring-fed mountain lake, was chosen because it was one of the few bodies of water in the area not subject to the warm, winter river runoff problem and that had sufficient depth. This eliminated significant amounts of trash that can provide very high and quite variable target strengths; e.g. tree bark trapping air bubbles. Several trips were made to Crescent Lake, with two producing usable data.

The ATP Project utilized an existing broadband sonar system that was originally designed for fish species identification. By utilizing this system, it was hoped to determine the feasibility of the proposed ATP estimation approach with more reliability than a paper design alone would offer. The sonar performed very well during all of the trials, however, this project was demanding levels of performance not considered in the original design. The sonar was specifically designed for fish identification by means of spectral analysis of the broadband echo reverberation from the fish. As such, a very high SNR –30 to -40 dB target was expected, and this target was to be detected by a wide bandwidth sonar front-end. This project, however, was attempting to measure the signal reflected by a very low SNR, -70 to -80 dB target -- the high frequency volume reverberation of the water column.

The following system descriptions review the test equipment employed during ATP field tests.

## 4.1 - Scientific Fishery Systems Broadband Sonar

The following Figure 8 illustrates the Scientific Fishery Systems Broadband Fish Identification Sonar:

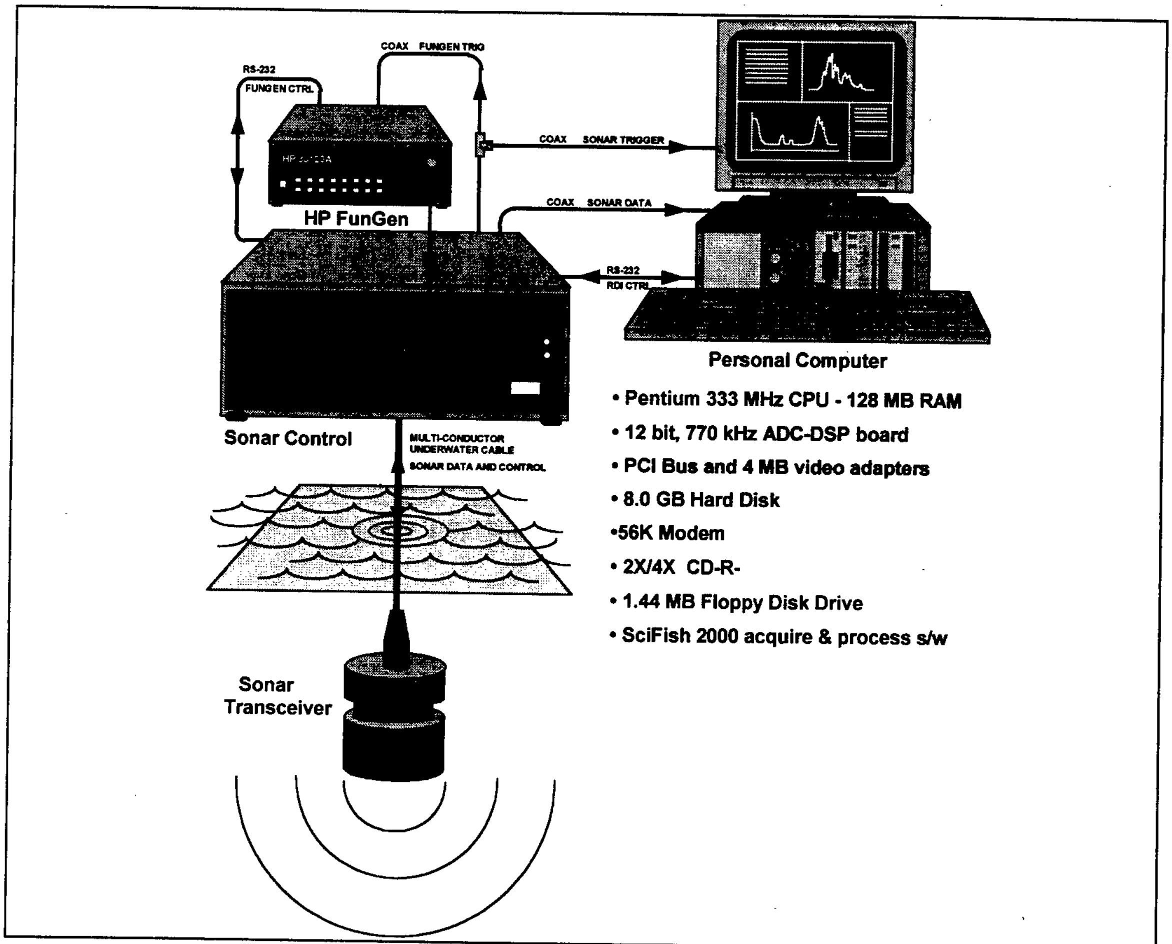


Figure 8. Sonar Transceiver Configuration

### 4.1.1 - Sonar Transceiver

The transceiver was specified to maximize acoustic bandwidth while maintaining functionality in terms of output power, beam pattern characteristics, noise immunity, and deployment capability. The transducer is a modified version of a 150 KHz ADCP transducer with some custom electronics in the transducer housing and in the topside vessel-mount (VM) chassis.

The disc-shaped ceramic transducer, with a center frequency is 153.6 KHz, produces a cone-shaped beam with a 3-dB beam width of 4.1° or a wider beam of 15°.

A narrow bandwidth was required for our application, so a high operating center frequency was selected. As delivered, the 6 dB receiver bandwidth is about 80 KHz (108 KHz to 189 KHz). The higher center frequency also generates a narrower beam for a given size transducer and reduces concern over common noise sources in the lower bands such as waves and shipping. Other significant operating parameters are summarized below:

Table 1. Broadband Transducer Specification Summary

| | |
|---|---|
| Resonant Frequency | 153,600 Hz |
| 3db Operating Band | 80 KHz (108 KHz to 189 KHz); Q = 1.9 |
| Active Surface | 177 mm diameter disc |
| Beam Pattern | 4.1° or 15° cone, sidelobes 13 dB down |
| Rated Power | 40 to 250 W transducer |
| Source Level | 216 to 226 dB re 1 μPa @ 1 meter @ 153.6 KHz |
| Transmit Sensitivity | peak TVR of 181 dB re 1μPa-m/V at 169 KHz |
| Receive Sensitivity | peak OCVR of -180 dB re 1V/μPa at 169 KHz |
| Deployment Depth | 20 meters with current cable, 1000m maximum |
| Physical Dimensions | cylinder 202 mm dia. by 225 mm tall; 11 kg in air |

Though the 3-dB bandwidth of the sonar is 45 KHz there is adequate signal-to-noise ratio for a bandwidth of 80 KHz (110 to 190 KHz) when high SNR targets are to be detected. One modification of this test system was to provide bandpass filtering to reduce the chance of saturation of the A/D via weather or man-made noise sources in frequencies well below our interest. The existing low pass filter combined with a high-pass filter set at 30 KHz provided significant immunity to this noise source.

Three types of transmit waveforms were programmed into the electronics. The available transmit waveforms include pulsed CW at any single frequency between 70 KHz and 200 KHz, linear FM sweep (chirp) over the entire range of frequencies with positive or negative frequency slope, and pseudo-noise (PN, phase coded) sequence

The CW mode emulates modern echo sounder and fish finder technology and provides a simple waveform for use evaluating ambient noise and adjusting receiver gain at fixed frequencies of interest. The FM mode provides a well-characterized broadband signal than can be matched filtered and whose returns are rich in spectral content. The PN mode is meant to impart maximum spectral energy into the water column for a given pulse length. These returns too can be matched filtered and, of course, are also rich in spectral content.

The transducer housing contains the analog electronics for transmit and receive transducer tuning, and the four-stage receiver amplifier. Ping transmit waveforms travel to the transducer housing and an analog signal representing the acoustic returns travels up the underwater cable to the Sonar Control Unit controls the sonar transmit cycle and sends the waveform signal. It also accepts serial ASCII commands from the PC to configure all aspects of the transmit waveform and provides trigger and raw signal to the processing platform over two coaxial lines. In the FM mode, the Sonar Control Unit receives its timing clock and waveform from the HP Function Generator. For CW and PN modes, the function generator provides a fixed timing clock only.

The transmitter's power is fixed but the receiver gain can be adjusted in four fixed steps that are set to 18 dB, 41 dB, 64 dB, and 87 dB. For most work, the gain was set to 41 dB, and a separate adjustable filter amplifier was set to the gain needed for each experiment. At any gain setting, preamp input impedance is much greater than the transducer output impedance allowing an estimation of the instantaneous sound pressure level from the digitized amplitude.

A cordage sling was fabricated to position the transducer over the boat's side along with floats to decouple the motion of the boat from the transducer. This was found to be significant with even small (~10 knot) wind fields. When fitted with the sling, the transceiver housing was aimed vertically downward suspended by ropes from the float.

### 4.1.2 - Processing Platform.

The computer processing platform is a customized "lunch-box" computer running Windows 95. The components of the platform are outlined below:

- DPS 9000 Lunch-box computer with 250 W power supply
- Intel Pentium II™ 333 MHz CPU with 128 MB DRAM
- 1 parallel port and 2 serial ports and 1.44 MB floppy disk drive
- 2X/4X CD-R drive (650 MB capacity)
- 8.0 GB hard disk
- 12 bit 770 KS/s ADC/DSP card with 486DX2/66 and 4 MB on-board DRAM
- 56K internal modem card with fax send/receive capability
- 1280 x 1024 LCD monitor and video adapter card with 4 MB SDRAM
- Touchpad and 101-key keyboard
- Windows 95® and *SciFish 2000* Interface & Processing software
- Matlab® v3.5m data analysis environment

The acquisition software used was a slightly modified SciFish 2000 data collection tool. This software controls the data acquisition board and the sonar transceiver. The data acquisition card is fitted with a 12 bit 770 KHz ADC, an external trigger input for the sonar trigger, and 4 MB of RAM, which holds the operating system, the custom executable kernels, and buffers the incoming digitized data. The on-board processor is an Intel 486DX2/66 which runs a simple operating system oriented towards data streaming to the ISA bus and simple signal processing such as FFTs and thresholding. This board was selected because of speed and a unique data-buffering scheme that maximizes the data transfer rates. The 486 chip keeps the cost low, compared to boards sporting special purpose DSP chips, and the native operating system provides all the functionality required for our real-time echo processing applications. This division saves time and money compared to the more complex DSP's native operating systems on some of the higher-end boards.

### 4.1.3 - Software Development.

The software development used the Visual Studio 97 (Visual Basic v5.0, Visual C++ v5.0). The engineering acquisition and processing software was compiled for Window 95 and the oscilloscope-like display and user interface is displayed at 800-by-600 resolution. The real-time samples are streamed, at full-resolution, to the hard disk for post-processing and any further analysis. An existing program was used to extract raw data to analyze it in general-purpose programs such as spreadsheets and mathematics manipulation programs such as MathCad and MatLab.

The software controls several parameters for the sonar through the Sonar Control Unit and environmental parameters and conditions. The user can also modify the operational range, the path and file name to which the data are being stored, and the thresholds used for preliminary detection of bottom and water column echoes.

## 4.2 - Applied Microsystems EMP 2000 Water Quality Monitor

SciFish used its CTD ocean sensor from Applied Microsystems Ltd. that has been used to support this project. The EMP 2000 is a self-contained, multi-parameter, programmable water quality monitoring instrument. The EMP 2000 owned by SciFish contains a depth sensor, a temperature sensor, and a current velocity sensor. The EMP 2000 features microprocessor based CMOS circuitry, a 4 1/2 digit analog converter (1 part in 40,000) and 128 KB of battery backed-up RAM for data storage.

The EMP 2000 relies on use of an 80x86 PC with low-level ASCII serial interface protocol running under MSDOS. The instrument's output is standard ASCII on an RS-232 data port that permits data transfer via 3-conductor cable. The baud rate is automatically selected with the maximum being 19,200. The data output may be configured to display either unprocessed integers, or computed engineering values. The EMP 2000 has the option of logging data continuously, by depth increments, by time increments, or logging individual scans.

The portable computer used to operate the EMP 2000 was a laptop computer running on its own internal battery supply. AML Total System was used to interface with the water quality probe.

# 5.0 - Field Test Results

Several short trips were made to conduct simple tests to checkout the operation and noise characteristics of the system. These are not documented here, nor are the trips where weather forced cancellation of the tests. The tests of interest occurred (all in 1999) on 2/18 (Hood Canal), 2/19 (Hood Canal), 3/5 (Crescent Lake), 3/19 (Crescent Lake) and 3/26 (Crescent Lake). The following paragraphs document the conditions and results of these tests.

## 5.1 – Tests Conducted

2/18/99: Deployed system off Toandos Point in excess of 400 ft. water in light rain and very light wind. Using Heart inverter to remove the vibration and noise of the generator. Observed ~100 KHz noise signal which appears to be a radiated component. Abandoned effort to concentrate on squelching the noise problem.

2/19/99: Having suppressed much of the noise deployed system between Misery and Toandos Points in deep water. Weather threatening, 37°F with light slush falling. Operating on inverter. Signals look much cleaner, however weather does move in (25+ knots wind) and transducer is banging against the hull. It appears the motion of the boat/transducer is affecting the signal levels adversely. Abandon station with only 55 pings data.

3/5/99: Launch on calm partly sunny day at Crescent Lake. Cool; snow level about 400 ft. above lake. Using inverter. Deployed in ~270 ft. water. Collected CTD data. Collected data over 3.5 hour span, with both wide and narrow beams and both receive transducers. All data appears to have a scalloping on it reminiscent of beat frequency. Analysis of this data showed contamination by noise, yet. It was later determined that the inverter was still radiating a ~96 KHz signal that on-board filtering could not remove.

3/19/99: Mostly clear day, but variable wind (5-15 knots) moving about Crescent Lake. Boat has ~±5-10° roll with ~3 second period depending on wind and wave action. Using the 4 KVA generator to remove inverter sponsored noise. CTD cast. Data has the expected shape with very minimal noise levels. Collected ~3 hours of data with a variety of transducer combinations and ranges. There is some scalloping, possibly due to vessel motion moving the transducer in spite of decoupling efforts. In post-processing data analysis, it is determined that the transducer was acting as a 2-part pendulum and only each 3$^{rd}$ ping had returns in the 4° beam. Standard Deviation of data is about 40 mV with a signal varying from ~1V to 0.1Vdc.

3/26/99: Plan is to float the transducer off the boat to further decouple its motion from the boat. Weather is very spring-like with sun and calm mixed with rain, hail and wind. Snow falls while the equipment and the boat are retrieved. Data is taken during episodes of absolute calm. Post analysis indicates successive ping to ping variation is now only about 5 mV. This confirms the need to keep the transducer stable and that the functional model will need multiple beams to adequately ensonify the field to account for vessel motion.

## 5.2 – Data Summary

The data shown below represent typical data from the two most significant collection trips: 3/19 and 3/26. They illustrate the raw data steps (several pings), mean step levels and the variability (via the statistical standard deviation) over 30 pings. It is significant that the 3/19 set has been selected on the basis of a minimum amplitude of received signal and that the 3/26 data is based on consecutive pings. This is indicative of the need for platform stability in the test situation. For the 3/19 data, 2 plots (**Figures 9 and 10**) are presented: showing the raw data steps and the mean and standard deviation of the data. The second set shows the mean and standard deviations and the 2nd shows the ratio of the standard deviation to the mean. This latter is an indication of the maximum possible range of the experimental setup due to SNR (signal to noise ratio). The maximum output of the system was measured at SciFish 2000 at 226 dB// 1µPa @ 1m with the added amplifier set to 250 Watts at this frequency.

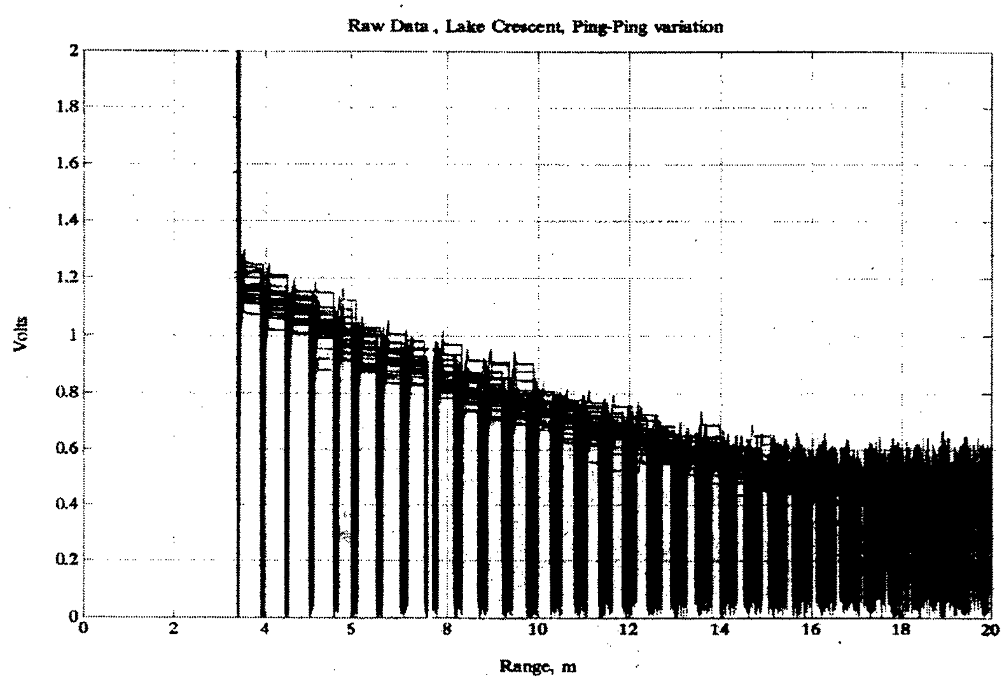


Figure 9. Raw Data from March 19, 1999

The steps are bracketed by transient lines, which are ignored. The actual data is alternating bi-polar, but shown here as an absolute value. We sampled each step over 500 times; thus data reduction is done by taking only one value per step. The data set is reduced in steps; first by taking the mean of the local set, as shown in **Figure 9**. An electronic instability is obvious as the transient lines fail to line up as range extends outward. This is due to an inexpensive oscillator used in this version of the hardware that will be replaced in the next generation with a crystal oscillator.

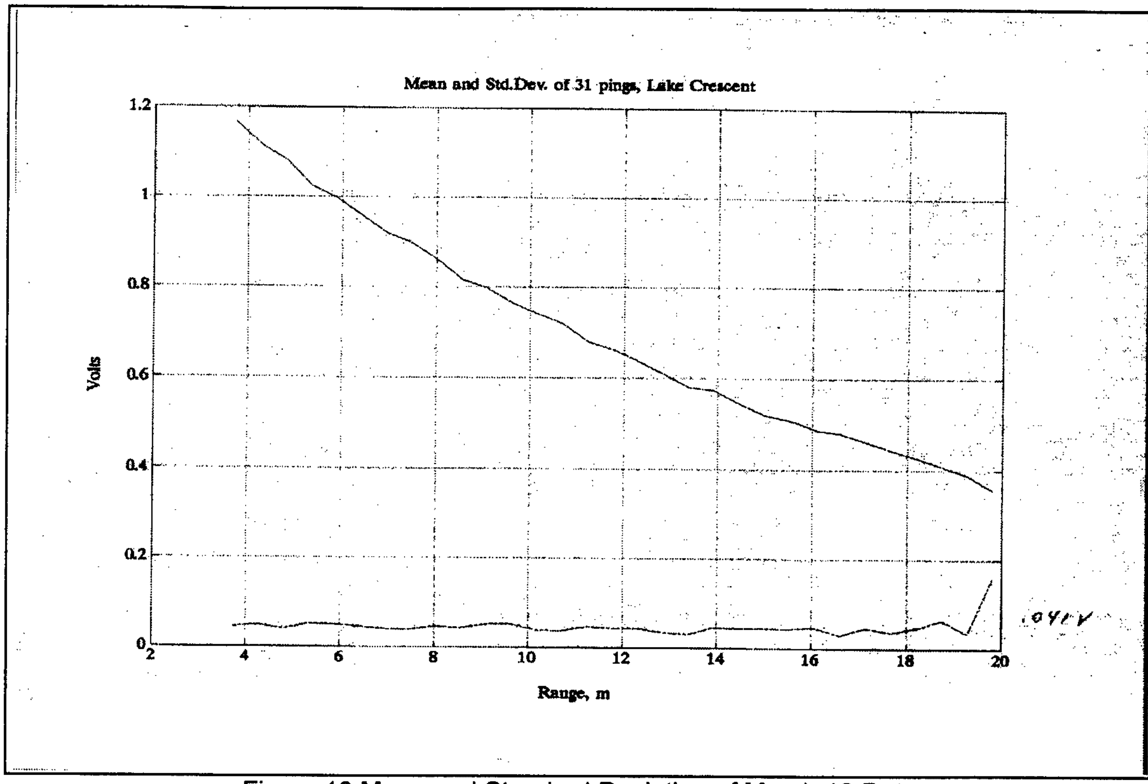


Figure 10.Mean and Standard Deviation of March 19 Data

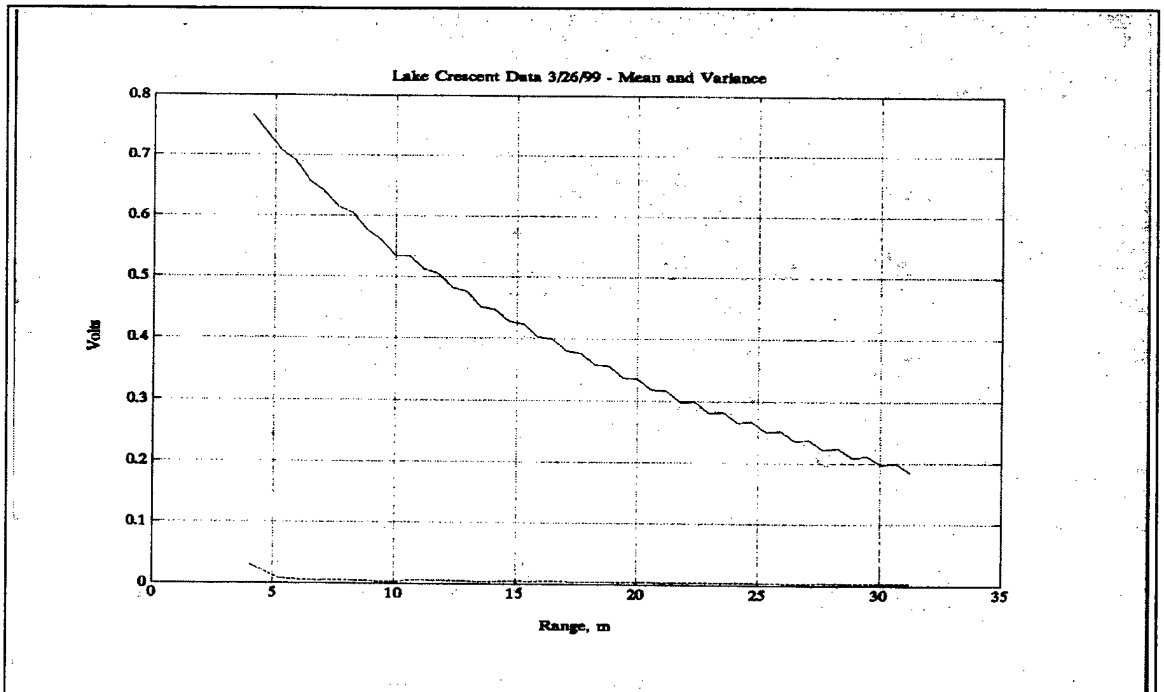


Figure 11. Mean and Standard Deviation of March 26 Data

The variation of the data in **Figure 10** is about 41 mV, ranging from about 5% to over 10% of the mean value of the output level. This represents an SNR of only 15 to 10 dB, which is minimal for normal data collection. Conditions during data collection entailed gusty and varying winds. Only 1/3 of the total data collected was suitable for analysis; the rest had levels significantly below these values as though the transducer was not receiving at the same area as the transmission pulse. This fact was born out in the data collected a week later under more calm and better controlled conditions.

**Figures 11 and 12** reflect the data taken on March 26. Note that the mean data appears decidedly smoother than the 3/19 data, and, more significantly, the variation in the data is one order of magnitude lower (5 mV). This data confirmed our suspicions concerning the motion noted during the 3/19 collection. **Figure 12** shows the ratio of standard deviation to mean value. This effectively represents our SNR and means our measurement has a variation of less than 2% at ranges out beyond 30m.

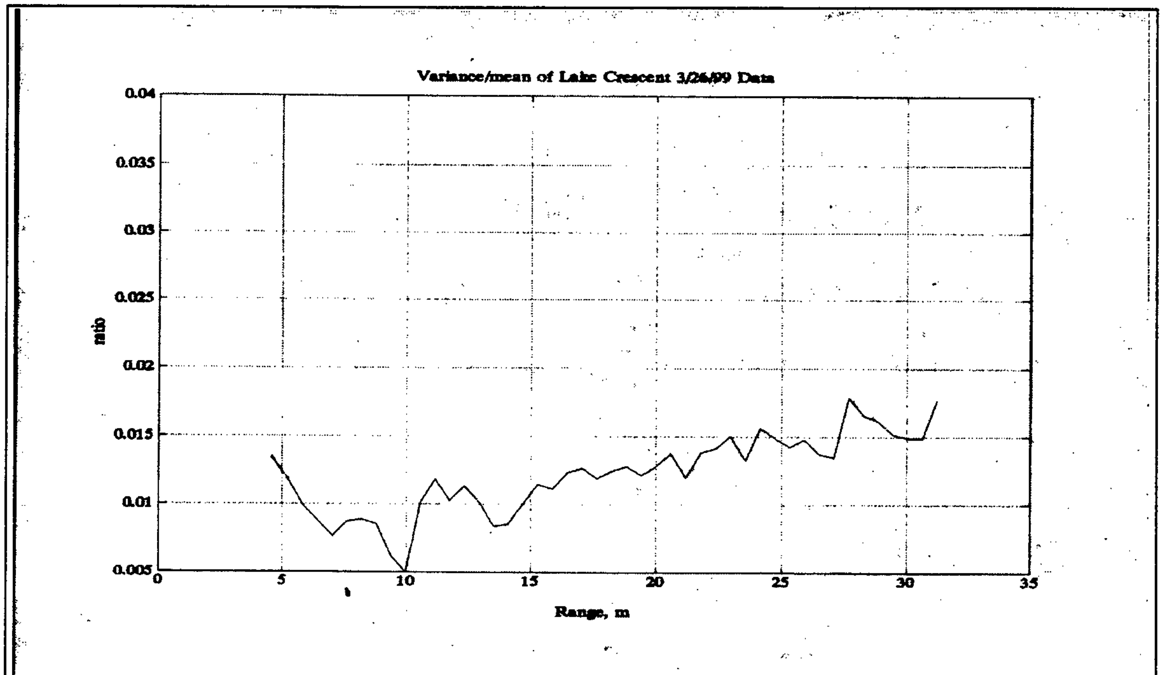


Figure 12. Effective SNR of System, ratio of Standard Deviation to Mean Values

## 5.3 - Field Test Conclusions

Several facts are evident from the experiments.

1. The data can be acquired with sufficient stability, but with current techniques and platforms, only near sea states zero to one. This will have to be addressed in the form of multiple beams and higher source levels in the fleet prototype models.
2. While the inverter is inherently a good idea in a small boat, it needs a Mu-metal enclosure to suppress spurious signals generated with the modified sine wave (MSW) AC synthesis approach. Since the electronics can have fixed gains of a factor of over 120, this method is

sensitive to radiated and conducted noise. For deployment on naval vessels, this is probably not an issue other than adherence to MIL standards for radiated and conducted noise.

3. The differential method works well to remove many poorly known or unknown sources of error known to interfere with more classical techniques. These include calibration of sources and hydrophones, knowledge of the scattering strengths and beampatterns of the volume scatterers, and background acoustic ambient noise. This does assume uniformity in transducer characteristics (with multiple beams) and gain settings and a sufficient volume of scatterers to average out the effects of specular reflections and uniformity of the distribution density of the scatterers.
4. From the plots, it appears that we can measure absorption to within .5% to ~1.7% in the range of 3.5 to 30 m. As the salinity measurement is of equal magnitude and made via similar constraints, we need to assume an equal portion of error on that measurement. When combining 2 independent statistical measurements, accepted practice is to RSS the values (RMS average) such that the expected temperature error grows to .75% to 2.5% of the mean value of absorption. At 1.5%, a mean value, the expected temperature error would be 0.08°C.

## 6.0 - Temperature Profiler Feasibility

In our previous work, we concluded that feasibility is likely given the acquisition of some critical components with sufficient dynamic range to examine a small phenomenon linked to a larger effect. In this current work, we have demonstrated that the measurements can be made with a difference system that offers some significant advantages in both acquisition and in overall cost. We have defined an ability to make the measurement, and projected a result based on those measurements when we can move to a more advantageous frequency range.

Previous methods can have difficulties with the lack of knowledge of the scatterers in the water column. We expect zones where the change in distribution of species of plankton in the water column would affect the results[v]. However, using the differential method the output will show an anomaly similar to detecting any significantly different target (e.g. a fish swimming through the beam) and that data point would be discarded.

### 6.1 Critical Component Discussion

The most critical components for any future system will be the transducers. It is obvious from this fieldwork that higher frequencies with higher source levels are needed. SciFish has recently signed an agreement with SciFish 2000, who produced our current transducers, toward closer cooperation on new development projects. They have current stock designs for 300 and 600 KHz transducers. The exact frequency for the temperature measurement is not as critical as the requirements for the salinity requirements (**Figure 1**). SciFish will work closely with RDI, or any other suitable vendor, to achieve the increases in source level to meet our requirements. Typically, transducers take 3-4 months to manufacture when there are non-standard specifications.

All other components are very much standard COTS, with low cost, low risk and high reliability.

## 6.2 Next Generation Design Constraints

- Increase frequency of operation to approximately 500 KHz to achieve higher absorption. Actual frequencies will be determined based on the exact requirements to obtain both temperature and salinity profiles in concert with availability of transducers with sufficient source level to obtain satisfactory measurement results and to increase the maximum range of the device.
- Produce a multi- or wider beam device to compensate for vehicle motion. Our experiments showed that transducer motion severely limited. If a wider beam, the source level will have to be increased to compensate for loss of DI.
- Subtract out the spreading loss (typically done in AGC circuits) to deliver an output directly proportional to absorption. This has an advantage in increasing range as it limits the needed dynamic range of the RMS to DC converter.

SciFish believes that all elements of this design concept are available commercially and reasonably priced. There is some advantage to the use of multiple beams because of an economy of scale in similar transducers that often starts with quantities of 2 or more. To be useful aboard fishing vessels, the cost would have to be less than $20,000.

## 6.3 Future Work

SciFish is proposing, in a separate document, the continuation of this Phase II SBIR work using the design guidelines of the previous section and the experience gained from the field and theoretical work already accomplished. The next generation system will:

- Operate at a number of higher frequencies to provide higher absorption values to measure - Increasing frequency increases the absolute absorption, thus the proportion of the signal above the spreading loss (20Log(range)) increases with frequency and the ease of measurement increases with frequency,
- Integrate a –20log(2r) amplifier to remove the spreading loss component and get an output reading directly proportional to absorption,
- Integrate over multiple small range cells to remove variability in the volume target scattering,
- Increase source level and, potentially, to have multiple, overlapping beams to gain reliable ping to ping data on rolling platforms,
- Operate in a number of different modes as the range is increased. The mode used in the current experimental setup was optimized for the highly sloped region of the spreading plus absorption loss curve that exists in the first 10 meters of range examined.
- Measure absolute temperature and absolute salinity at the transducer face as a ground truth reference.
- Be a stand-alone system, capable of installation on a naval vessel for further testing.

# 7.0 – Commercialization

Potentially one of the most significant, and affordable, fishing by-catch reduction tools is based on use of the thermal structure of the water column. It is known in the fishing community as Temperature Directed fishing. Japanese, Russian and Norwegian fishing fleets have been using this technique for several years, and it is just beginning to come to the attention of American fishers. While fishers do not need the resolution of a military system (1°C is easily sufficient), the ability to fish on the thermal structure has a strong financial incentive.

SciFish believes that these systems would not be significantly different from those needed by the Navy, as the process would be the same. Since fishers have a lower resolution requirement, they would be able to obtain greater range from the same system, as the SNR requirement would be relaxed. This would render an economy of scale for the production of the devices for all potential customers. Alternately, wider beamed systems that might be less expensive (fewer transducers) that would operate under less stringent SNR conditions would have a similar range with less cost. These devices will be considered for physical utility, and ease and ability to incorporate into existing software and hardware. The output can also easily be incorporated into our Fisherman's Associate software (a current commercial product) for immediate use in the fishing fleet.

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