

NSWC TR 89-264

PMUWS ACCEPTANCE TESTS

BY GREGORY F. PAGE

UNDERWATER SYSTEMS DEPARTMENT

12 DECEMBER 1989

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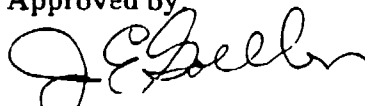
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FOREWORD

This task was sponsored by Naval Sea Systems Command (NAVSEA), PMS-407, under the Mine Improvements Program, task number NAVSEA-63-89-13A08R1. The job order number was 9U15DD25H. The purpose of the task was to develop a pressure/3-axis magnetic recording and playback system in support of bottom mine evaluation. This report covers the laboratory and in-water tests performed on the Pressure Magnetic Underwater System (PMUWS) sensor package manufactured by the Dowty Corporation. Subsequent reports will cover the shore recording system and the playback system that will be developed for the Naval Surface Warfare Center's (NSWC) Helmholtz Coil Facility in Building 203.

Approved by:



DR. J. E. GOELLER,
Deputy Department Head,
Underwater Systems Department



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CHAPTER 1

NEED FOR A PRESSURE/MAGNETIC RECORDING SYSTEM

There is a continuing effort to improve Naval Surface Warfare Center (NSWC) Code U42's methodology for laboratory testing magnetic/pressure mine Target Detection Devices (TDDs). Currently, U42 has separately recorded libraries of magnetic signatures and pressure signatures of target vessels. All of U42's laboratory simulation and computer modeling work first determines the target actuation performance of each channel separately. Second, assumptions are made about the percentage of fires that will be lost due to the timing coordination algorithm used to make fire decisions (which are based on the relative time of occurrence of the two channel actuations). These assumptions are based on previous experience with test mines in the field. We currently have no way of knowing whether or not our assumptions are correct for a particular combination of TDD, target, and pressure background that we may be testing or modeling at the time in the laboratory. Thus, we have no way of laboratory testing the effectiveness of the particular timing coordination algorithm used with magnetic and pressure channels of a TDD under different conditions. Only field data can give us the information we need. Although this deficiency has been pointed out many times over the years, no economical means of acquiring simultaneous magnetic and pressure data with good tracking was available at the time. Also, the tracking information for magnetic recording has only been available over the past few years.

In summary, there is a need in U42 for instrumentation quality recording of the pressure and magnetic signatures of targets with accompanying target track information. This information is required primarily to support technical evaluation (TECHEVAL) laboratory target signature playback tasks and, secondarily, to support future TDD algorithm development tasks.

CHAPTER 2

SYSTEM REQUIREMENTS

DISCUSSION

Bottom mine sensors usually have band pass frequency response bracketing the known frequencies of target signatures. This is to keep out all other signals which will only disturb the target signature acquisition process. In addition, the sensors may have resolution just adequate to resolve small target signatures. Peak pressure amplitudes from 3-knot targets can be in the neighborhood of 0.1 inch of water. Peak amplitudes for small and/or degaussed vessels can be on the order of 10 nanoteslas.

The recording and playback systems used for bottom mine evaluation should have wider signal bandwidth than the TDDs under test. This is true because we do not want to double filter the signal a detection systems sees (once on recording and once inside the TDD on playback..

For resolution, the smallest signal requiring detection should cause an excursion through many, say at least 10, units of resolution.

For the above reasons, U42 has established a design goal of 0.5 nanoteslas magnetic resolution and 0.01 inch of water pressure resolution. The minimum bandwidths were chosen to be dc to 1 hertz for the magnetic channel and 0.002 to 1 hertz for the pressure channel. It would be desirable to have dc response on the pressure channel, but it is difficult to get 0.01 inch of water resolution with dc response at typical mining depths; this requires the sensor to resolve about 6 parts per million of full scale. Thus, dc response on the pressure channel was not made a requirement. This allows a wider range of design options.

Another difficulty in designing a bottom pressure sensor is achieving acceptable levels of temperature sensitivity. Bottom water temperature in the Hampton Roads Channel has been observed changing 2 degrees over a few minutes. Temperature fluctuations of this amplitude and rate should not cause false pressure outputs much greater than 0.01 inch of water. All previous pressure sensors used by U42 have been housed in a nonmetallic barrel about 2-feet in diameter and 2-feet high. This barrel provides both mechanical protection and thermal isolation for the pressure sensor. An analysis presented in the appendix of Reference 1 of the data from temperature response tests on the temperature shield (presented in Reference 2) indicated that the shield provides at least a factor of 1000 attenuation of external temperature fluctuations in the frequency range of interest. This allows for relaxing the temperature sensitivity requirement on the pressure sensor, helping reduce sensor complexity and cost.

Another area of concern is the means of transmitting and recording the sensor signals. To avoid drift and noise induced by cabling, connections, and shore electronics, it is best to sample the data in the water and send the information back to shore digitally. Also, since U42 is now doing most of its data analysis digitally, it is highly desirable to have the sensor package output digital samples so that they can be packaged with the tracking records and stored in some popular computer file format.

Finally, it would be best for the system to use only two wires. This would allow the flexibility of using any type of cable already planted or on reserve at the NSWC Fort Monroe and Fort Lauderdale Test Facilities. Still acceptable, but less flexible, is the use of three conductors. The four pressure sensors at Fort Monroe and the two at Fort Lauderdale are now on three conductor cables. Thus, an upgrade of the pressure-only sensors to pressure/3-axis magnetic would not incur any new cabling costs. However, to extend the range of candidate systems, it was decided not to put a 3-wire maximum requirement on the developer, since the main thrust of the effort was to acquire and validate the sensor package. Modification of the cable interface circuitry was left for a later effort. A requirement of using eight conductors or less was put into the request for proposal (RFP).

SENSOR PACKAGE REQUIREMENTS

Table 1 contains a list of requirements that were in the RFP for the sensor package.

TABLE 1. REQUIREMENTS FOR THE SENSOR PACKAGE

Magnetometer Specification:

1. Triaxial measurement capability.
2. Minimum static field range of 100,000 nanoteslas.
3. Minimum dynamic range of $\pm 10,000$ nanoteslas.
4. Resolution down to 0.5 nanoteslas.
5. Sensor self noise less than 0.5 nanoteslas.
6. Loss of orthogonality less than ± 0.1 percent.
7. Response to signals above the $1/2$ Nyquist sampling frequency should be at least 20 dB down from midband response.

Pressure Sensor Specifications:

1. Minimum dynamic range of ± 30 inches of water.
2. Resolution down to 0.01 inch of water.
3. Minimum frequency bandwidth of 0.002 to 1.0 hertz.
4. Sensor self noise cannot exceed 0.01 inch of water.
5. Temperature sensitivity less than 0.2 inch of water per degree Celsius.

Telemetry Specifications:

1. The sensor sample rate must be fixed within or settleable within a range of three to five samples per second.
2. Electrical connections must be via a single electrical connector requiring a maximum of eight electrical connections.
3. System must output all samples on a single line or a line pair in a format compatible with a standard serial format such as RS-232, RS-422, or RS-485.
4. The assembly must be capable of operating when connected to a heavy duty submarine cable up to 20,000 feet long. These cables are coax or 3-, 10-, or 16-conductor twisted lead cables. Typical electrical parameters are 1 ohm/1000 feet, 16 nanofarads/1000 feet, and 80 ohms characteristic impedance.

Other specifications:

1. Sensors and telemetry electronics must reside in a single waterproof housing.
2. Housing must be able to withstand water depths up to 200 feet.
3. No housing dimension can exceed 24 inches.
4. Total system weight should not exceed 200 pounds.
5. System must operate on dc voltages not to exceed 100 volts.
6. Assembly power consumption must not exceed 30 watts.
7. The sensor assembly must operate within specifications in water up to 100 feet deep.

CHAPTER 3

PMUWS DESCRIPTION

The only company to bid on the above requirements was Dowty Corporation, a British firm, through their American affiliate, Humphreys, Inc.. The proposed system was a modification of the standard Dowty Magnetic UnderWater System 3 (MUWS3), which is a 3-axis magnetic sensor package. There is still some discussion about what Dowty will call the modified MUWS3, but U42 is currently calling it the PMUWS.

EXTERNAL VIEW

An external view of the PMUWS is presented in Figure 1. The pressure sensor is on top of the unit. Notice that the positive Z axis is pointing down. This orientation was used to provide a positive output for the Earth's field in the Northern Hemisphere. The PMUWS is made of yellow and black plastic and is fastened together with stainless steel hardware.

MANUFACTURER'S SPECIFICATIONS

Some of the more important manufacturer's specifications are contained in Table 2.

When the above specifications were received in response to the RFP, it was noted that there were two specifications that did not meet the RFP requirements. First, the 0.5 degree nonorthogonality was larger than the requested 0.1 percent requirement in the RFP. The author decided that 0.5 degrees nonorthogonality was acceptable since 0.5 degrees is about 10 times better than typical TDD magnetometer requirements. Second, the - 20 dB at 2.5 hertz specification for the magnetic channel was 0.5 hertz higher than the requirement. Since there is very little energy in the magnetic signal above 1 hertz, this small departure from the requirements was deemed acceptable.

In addition, when the PMUWS was delivered, the accompanying manual had the letters "RMS" appended to the specification of 0.01 inch of water self noise on the pressure channel. Since there was an error of omission in the RFP specifying the type of units and since the assumption about the requirement is reasonable, it was decided that 0.01 inch of water root mean square (RMS) was acceptable.

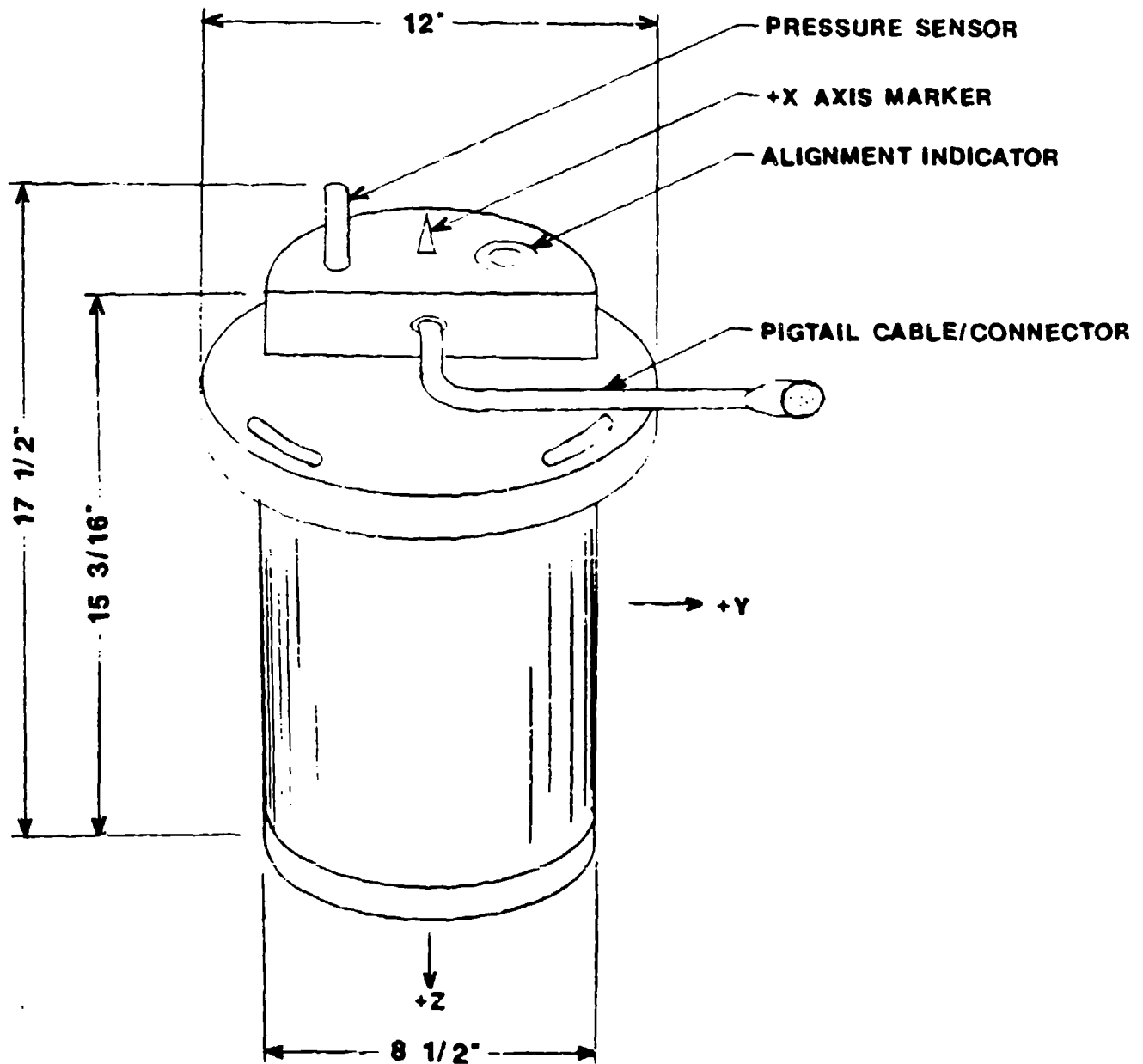


FIGURE 1 EXTERNAL VIEW OF PMUWS

TABLE 2. MANUFACTURER'S SPECIFICATIONS

Electrical

Current	350 milliamperes $\pm 5\%$
Voltage across sensor	30 volts $\pm 5\%$
Communications	RS485 (Serial Bus Mode)
Baud Rate	9600

Magnetic

Maximum field prior to analog saturation	$> \pm 120000 \text{ nT}$
Maximum back off range	$> \pm 100000 \text{ nT}$
Minimum back off increment	$< 100 \text{ nT}$
Digitized magnetic output	
Range A (no back off)	$\pm 100000 \text{ nT}$
Range B (with back off)	$\pm 16384 \text{ nT}$
Resolution	
Range A	$< 4 \text{ nT}$
Range B	0.5 nT
Accuracy--all ranges	$\pm 1 \text{ nT}$ or 1% of reading, whichever is greater
Analog Bandwidth	dc to 1 hertz (-3dB)
Anti-alias response	At least -20 dB at 2.5 hertz
Axis orthogonality	$< \pm 0.5$ degrees in any axis
Sensor self noise	$< \pm 0.5 \text{ nT}$ in d.c to 1 hertz bandwidth
Self test accuracy	$< \pm 0.25\%$

Pressure

Static Range	4 Bar
Dynamic Range	± 50 inches of water
Resolution	< 0.0016 inch of water
Filter bandwidth	dc to 5 hertz
Self noise	< 0.01 inch of water (RMS)
Temperature drift	< 0.2 inch of water/degree Celsius

Telemetry

Sample rate	Up to 10 times per second on interrogation from shore computer
Cable length	Up to 20,000 feet of shielded, twisted pair cables. Loop resistance < 40 ohms, $Z_0 < 80$ ohms. Shore power supply voltage to be adjusted to suit the loop resistance.

Temperature Range

Temperature range within which the systems is within specifications	0 degrees to $+ 30$ degrees Celsius
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Mechanical

Maximum Depth	200 feet
Gimbal freedom	15 degrees vertical error
Weight	40 pounds, approximately

FUNCTIONAL BLOCK DIAGRAM

Figure 2 is a functional block diagram of the PMUWS. The design is straightforward. The underwater connector contains the bipolar power pins, two RS-485 communication pins, and the three analog outputs of the magnetometer. The backoff and gain can be controlled from shore. The backoff is the amount of static field to be subtracted from the measured field before applying gain to the signal. After the backoff command is issued, the PMUWS sends the values of the amount of backoff back to shore for storage in data file headers.

COMMUNICATIONS AND OPERATION

The PMUWS was delivered with a manual that describes the command set and the structure of the return data frame, all of which are sent over the two communications (COMMS) lines. There are commands to perform self calibration and to set the channel gains. When the PMUWS is powered up, it comes up in the coarsest range setting. The magnetic range is large enough to read the Earth's magnetic field, and the pressure range is large enough to read the absolute pressure due to the atmosphere and the column of water over the unit. There is a backoff command which tells the PMUWS to read the current fields, send the values back to shore, and subtract those readings from all subsequent readings. After this, the gain can be selected to apply to the ac signal that remains. This method provides for better resolution than would be possible if the dc components were included in the measurement.

After the PMUWS is initialized, a sample is sent only if requested by the computer controlling the PMUWS. A personal computer (PC)-resident controller designed by the author uses a counter-timer, plug-in card to generate 0.250 second interrupts. These interrupts initiate an interrupt service routine that sends the sample request to the PMUWS. The values of these samples are stored in various files on the PC.

SIGNAL CONVERSION AND RANGES

The digital-to-analog converters in the PMUWS are 16 bit. They are used in a bipolar fashion giving a range of ± 32768 counts. The ranges and resolutions achieved by the PMUWS depend upon the analog gains selected. The following is the menu of settleable ranges:

<u>Magnetic (nT)</u>		<u>Pressure (Inches H₂O)</u>	
<u>Full Scale</u>	<u>Resolution</u>	<u>Full Scale</u>	<u>Resolution</u>
$\pm 100,000$	3.052	± 2000.29	0.0386
$\pm 16,384$	0.500	± 263.36	0.0837
$\pm 3,276$	0.100	± 52.67	0.001607

Dowty engineers stated that, although the PMUWS can be set for the most sensitive magnetic range (0.100 nT resolution), the company is not now formally specifying it as a feature of the PMUWS. This range would not be used during wild ship ranging because too many targets signatures would clip. On the other hand, it could be the range of choice for dedicated ranging against most combatants.

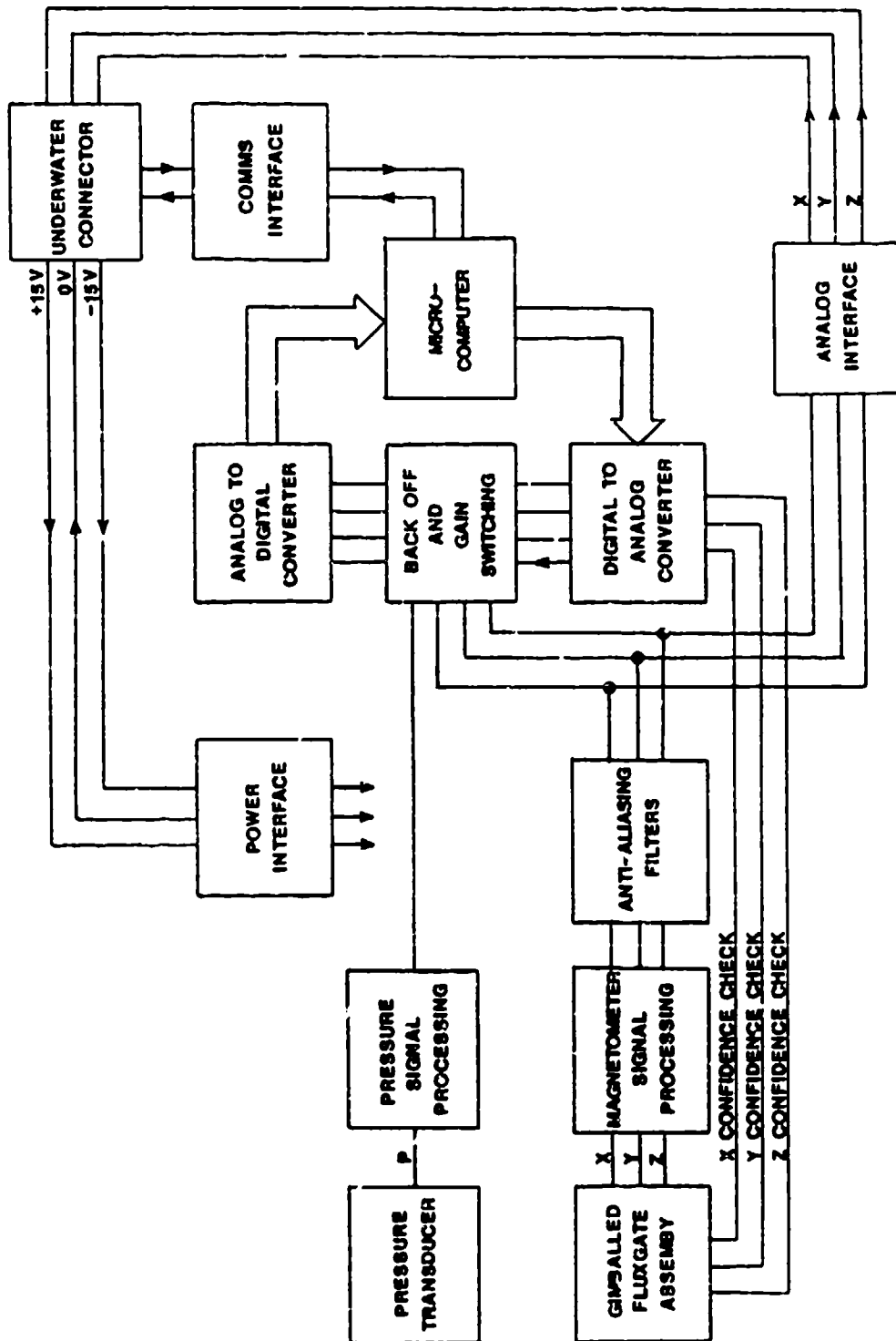


FIGURE 2. PMUWS FUNCTIONAL BLOCK DIAGRAM

The high-gain magnetic range was tested in this evaluation because of the potential usefulness of the high-gain magnetic range and because that range allows us to more closely test the PMUWS magnetic channels for self noise.

MAGNETOMETERS

The magnetometers are of the fluxgate type and are mounted in a gimbal which preserves verticality of the Z axis to within 0.25 degrees for case tilts up to 15 degrees. The nonorthogonality of each of the three sensor elements as a component is 0.1 degrees. Due to tolerances in mounting the elements in their fixture, the orthogonality specification for the triaxial system is 0.5 degrees. Dowty engineers stated that tolerances tighter than this would necessitate a more expensive mounting system and expensive additional testing.

The chamber which contains the magnetometers is filled with a damping fluid. Dowty views all but the most rudimentary facts about their magnetometer and its signal processing to be commercial proprietary. From the point of view of U42 needs, this is acceptable since we will use the PMUWS as a nonserviceable, calibrated instrument with requirements on the overall transfer function.

Following the proprietary signal processing is a set of three, 3-pole Butterworth anti-aliasing filters with corner frequencies at 1 hertz, one for each magnetometer channel.

Also, it is possible to perform additional filtering digitally. This is done by specifying at system setup time the number of digital samples to take for each data frame. These samples are then averaged to yield a filtered result. At 4 hertz, up to 512 samples can be requested. Requesting more than 512 samples causes an error condition. The value of 512 samples per frame was used in this test program.

PRESSURE CHANNEL

The pressure sensor is a 4.0 bar absolute unit manufactured by the Druck Company. The housing is made of titanium. The information from Dowty stated that the pressure sensor was based on "advanced silicon, micromachined, sensitive elements configured as a bridge network."

The pressure sensor is dc coupled, thus providing full measurement of the static pressure due to the atmosphere and water column, as well as providing complete recording of tidal variations. There is a single pole analog lowpass filter with a corner frequency of 5 hertz following the pressure sensor. In addition, the above-mentioned digital filtering with 512 samples was used.

CHAPTER 4

TESTS AND RESULTS

TEST HISTORY

A test plan³ was published in February 1989. The plan described the PMUWS and the intended testing methodology and schedule. During the course of the test program, the need for additional tests became apparent. Thus, the actual test program became a superset of the one proposed.

The PMUWS was received by U42 in early April 1989. The first order of business was to power up the PMUWS and attempt to establish communications with the PMUWS computer system over an RS485 line from a PC. This was done by modifying a PMUWS checkout program written by Dowty in Pascal. After the communications with the PMUWS was established, some of the checkout routines were run and everything appeared to be functioning properly.

The communication procedures and the necessary portions of the PMUWS control procedures were ported over to the U42 test program written in BASIC. Procedures previously written for recording the PMUWS data frames were tested and debugged. This recording software was then tailored for recording the results of the upcoming laboratory tests.

Laboratory tests started in late April and continued through the end of May. At that time, the PMUWS was transported to the NSWC Fort Monroe Test Facility for preparation for planting in the Hampton Roads Channel in 70 feet of water.

The PMUWS was planted in the Hampton Roads Channel on 8 June 1989. The PMUWS was operated as a component of the U42 Pressure/Magnetic (PMAG) recording system. During June, July, and August, the PMAG system was operated for 12 days of wild ship ranging with a total of 100 target signatures acquired. Roughly half of these targets had athwartship distances less than 350 feet.

On 23 August 1989, the PMUWS was recovered for a corrosion inspection and replanted on the same day. On 20 October 1989, the PMUWS was recovered for a retest of the pressure frequency response and to test the interchannel signal susceptibility. The following paragraphs discuss the methodology and results for each test performed on the PMUWS.

PRESSURE SELF NOISE TEST

For the pressure self noise test, the PMUWS was placed inside a large metal test chamber which virtually eliminates all sources of pressure noise other than thermal drift. The chamber had ports for attaching a precision pressure monitor, for

bringing out the PMUWS conductors, and for getting pressurizing gas into the chamber. The chamber was pressurized up to 20 psig and sealed off. The precision pressure gauge (Paroscientific Depth Gauge Model 8030) registered some slow drift of the pressure in the chamber during the tests. The pressure output readings of both the PMUWS and the monitor were recorded into computer files.

Figure 3 displays three pressure waveforms. The lower waveform is for the Paroscientific pressure monitor. The center waveform is a lowpass filtered version of the Paroscientific waveform; this signal represents the thermal drift of the pressure in the test chamber. The upper waveform is for the PMUWS, with the thermal drift subtracted out. Notice that the PMUWS noise stays mostly within the ± 0.01 inch of water region. The total self noise test lasted 768 seconds. During this interval, there were five excursions of the PMUWS outside 0.02 inch of water, with none as high as 0.03 inch of water. The RMS value of the noise was very near 0.005 inch of water. Thus, the PMUWS pressure self noise is well within the specification requirement of less than 0.01 inch RMS of water.

Further investigations into specifying noise for an instrument revealed that a better method than specifying an RMS value would be to record the noise for a duration corresponding to the required highpass corner period. Then define the noise to be the maximum value between any two points in that record. This would contain all the signal energy in the channel bandwidth including low frequency drift. Thus, for the PMUWS, since the corner frequency is 0.002 hertz, the required recording time is 500 seconds. A word of caution is worthwhile here. First, the noise measurement should be made with either constant pressure (which is problematic) or the applied pressure should be measured by some reference sensor and subtracted out from the test systems noise output. Second, if temperature sensitivity is called out as a separate requirement (as it is with the PMUWS), then the noise measurement should be made in isothermal conditions so that thermal drift does not contribute to the noise.

This new definition of noise is more stringent than the RMS definition. Recall that the purpose of specifying maximum noise levels is to ensure that noise does not disrupt detection of 0.1-inch-of-water signatures. Also, the longest duration of the negative portion of a tactical pressure signature is about 100 seconds. Therefore, a total self noise of 0.05 inch of water peak-to-peak (p-p), according to the above definition, over a 500-second interval will ensure that the target signature is not corrupted by the recording systems self noise.

It is proposed that this new definition of noise be adopted for both the pressure and the magnetic channels. The self noise test records of the PMUWS pressure channel were reviewed, and six records lasting 500 seconds or longer were found. The minimum-maximum pairs for these records were: (-0.021, 0.018), (-0.023, 0.011), (-0.036, 0.009), (-0.012, 0.011), (-0.029, 0.010), (0.009, 0.025) inches of water. The range of p-p values is 0.023 to 0.045 inch of water. It should be noted that some of the measured noise is due to U42 instrumentation. It is estimated that this component is as high as 0.02 inch of water. In any event, the current configuration of the PMUWS passes the new self noise requirement for the pressure channel.

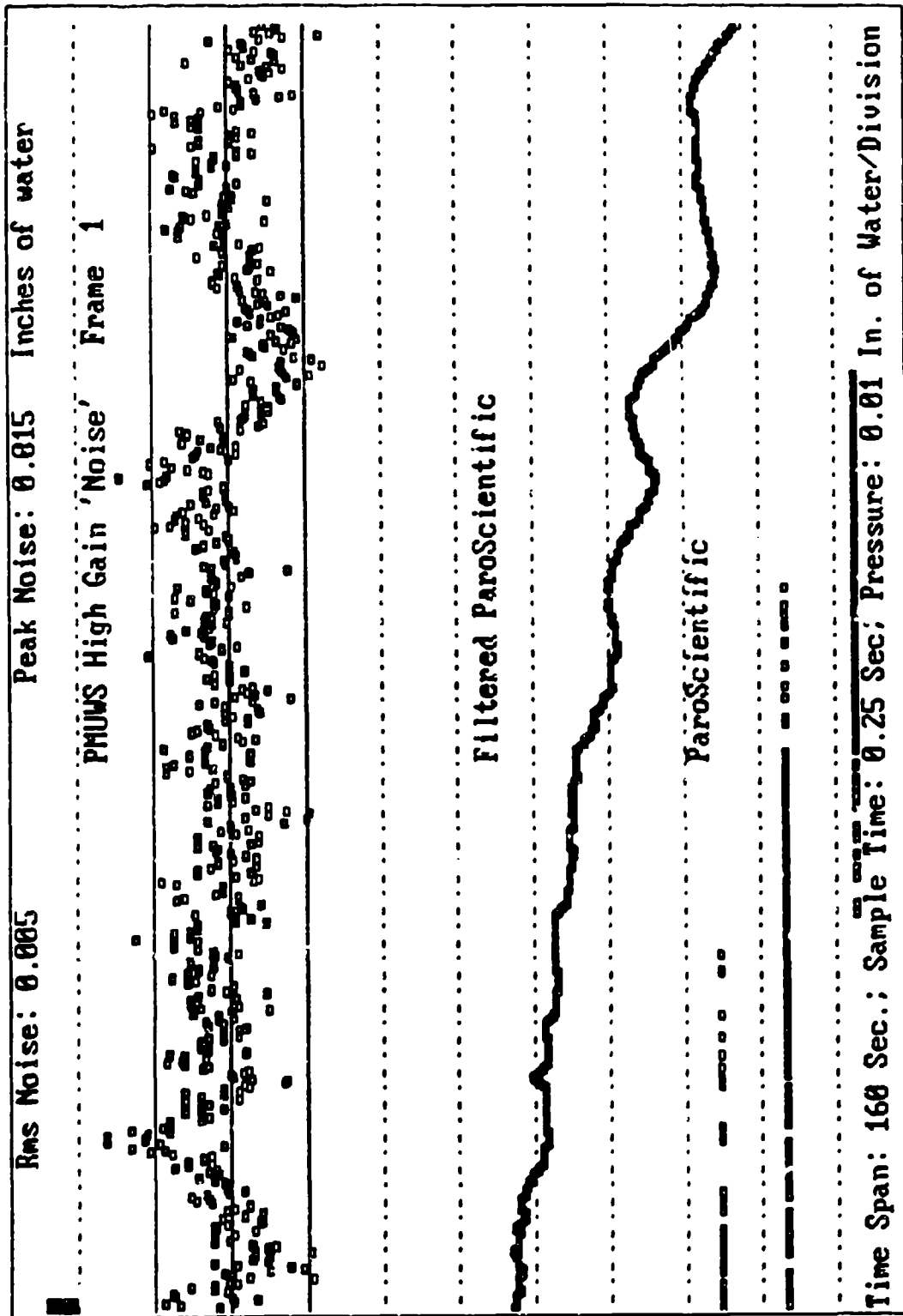


FIGURE 3. PRESSURE SELF NOISE WAVEFORM

PRESSURE RESOLUTION TEST

While the PMUWS was still in the test chamber, the polyethylene hose leading to the close-off valve was squeezed firmly enough to cause the mean of the monitor and PMUWS waveforms to offset about 0.01 inch of water. The two waveforms tracked very well.

PRESSURE CHANNEL TEMPERATURE SENSITIVITY TEST

It is important that the PMUWS pressure sensor not display excessive temperature sensitivity. In-water temperature changes of 2°F over a few minutes have been recorded at the NSWC Fort Monro Test Facility. The output of the PMUWS, inside of the temperature shield, should be less than 0.01 inch of water in response to such changes. The temperature shield enclosing the PMUWS attenuates the external temperature changes by at least a factor of 1000 in the frequency band of concern.

The test was performed by first inserting a temperature probe into a pressure sensor port and taping it in position. Then an ice pack was placed over the sensor and its surrounding area. The ice pack was left on for about 30 minutes and then removed. A plot of the resulting temperature and pressure waveforms is given in Figure 4. The false pressure output rises and then falls in response to the decreasing temperature. This type of response is characteristic of a highpass filter.

The first section of the temperature waveform can be modelled by a constant plus and exponential of amplitude -24.0°F and a time constant of 200 seconds. The circles on the first section of the temperature waveform represent this function.

If the PMUWS is modelled as a discrete single pole highpass filter, then the output will be a sum of a constant time as decaying exponential with the 200-second temperature time constant and a constant times another exponential with the time constant of the pressure-temperature system impulse response function. The best fit to the output function was achieved with a single-pole, highpass filter transfer function with a sensitivity of 0.14 inch of water per degree Fahrenheit and a time constant of 1000 seconds. The circles on the first section of the pressure output waveform represent that function. The difference in the waveform shapes is probably due to the fact the highpass filter is a distributed system and that there is some lowpass filtering experienced also.

The values of 0.14 inches of water per degree Fahrenheit (0.25 inch of water per degree Celsius) is 25 percent over the requirement of 0.2 inch of water per degree Celsius.

PRESSURE DYNAMIC RANGE AND ACCURACY TESTS

On both the low- and high-sensitivity dynamic ranges of the pressure channel, the pressure applied to the PMUWS was taken up to the plus and minus limits of the range. In all cases, the PMUWS reading and the monitor reading agreed to within one-half of a percent of the reading. Note that an accuracy specification for the pressure channel was inadvertently omitted from the contract specifications. Also, Dowty provided no accuracy specification for their pressure channel whereas they did provide one for their magnetic channels.

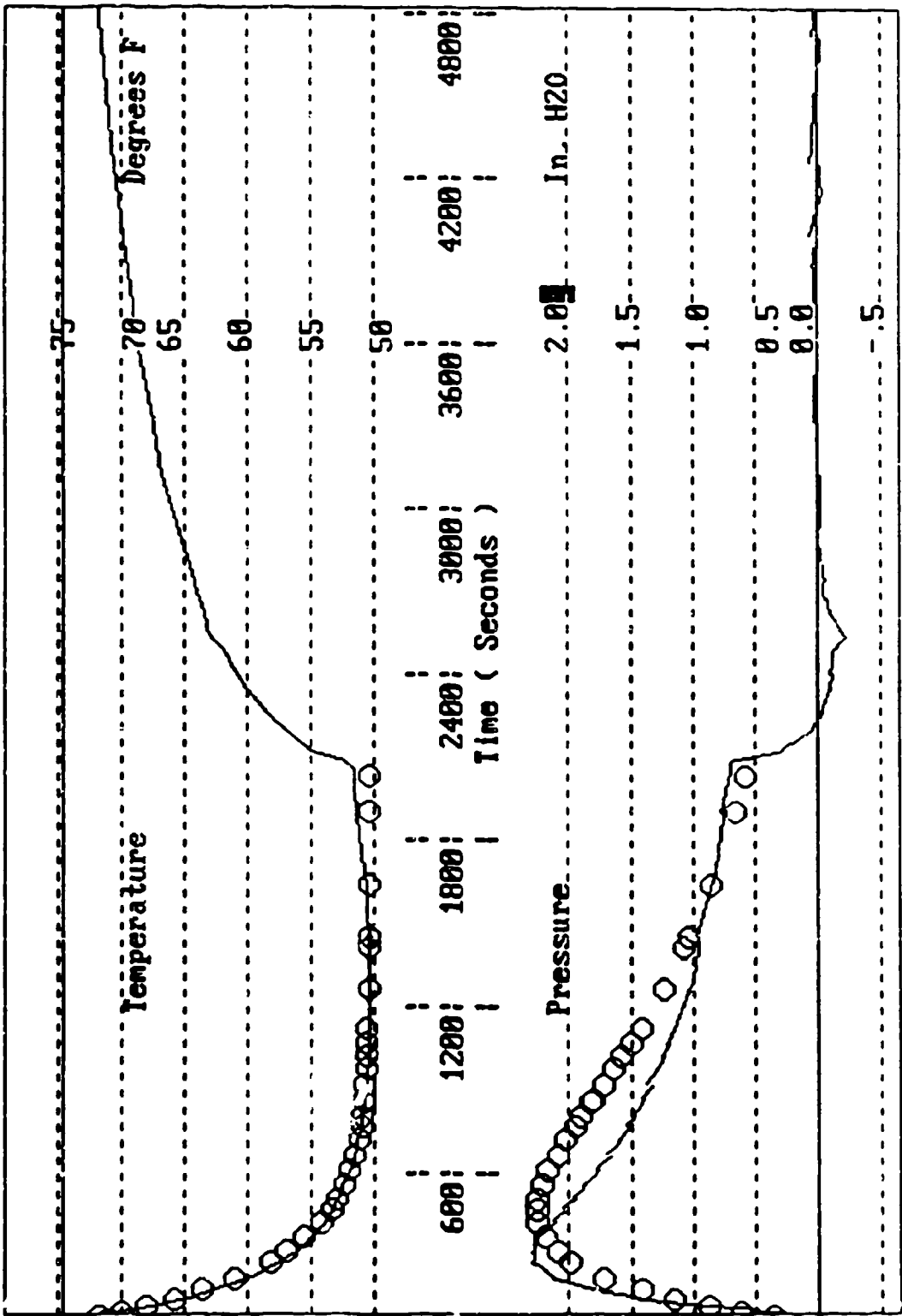


FIGURE 4. PRESSURE CHANNEL TEMPERATURE RESPONSE

A good specification for the pressure channel accuracy would be the one similar to the one that Dowty cites for the magnetic channels: 0.02 inch of water or 1 percent of reading, whichever is greater for all ranges. The test results indicate that the PMUWS pressure channel meets this specification. The error of omitting an accuracy requirement for the pressure channel should be corrected in the RFP for any future buys of pressure/magnetic sensor packages.

PRESSURE FREQUENCY RESPONSE TEST

Sinusoidal pressure variations were applied to the pressure test chamber with the PMUWS inside. The pressure variations were produced by a Schwiem Model 1095-0001 pneumatic pressure controller driven by a signal generator. This controller can produce pressure variations out to 5 hertz. A Gulton pressure transducer model GS 603 was used to provide flat frequency response out beyond 5 hertz. Sinusoidal pressure variations were applied to the PMUWS pressure sensor.

Two frequency response tests were performed: one sampling the PMUWS at 32 hertz and one sampling at 4 hertz. The 32-hertz test was performed to provide frequency response out to 5 hertz. For the 32-hertz test, the frequency was set to various values in the range of 0.005 to 4.0 hertz. For the 4-hertz test, the frequency was set to various values in the range of 0.005 to 1.0 hertz. As shown in the 32-hertz curve of Figure 5, the PMUWS frequency response is indeed flat out to about 1 hertz, where the effect of the pressure channel 5-hertz analog lowpass filter starts to be felt. The 4-hertz curve falls off faster than the 32-hertz curve above 0.2 hertz, but it is still registering 95 percent of the signal value at 1 hertz.

The dc coupling of the pressure channel, together with the above measurements, demonstrates that the PMUWS has the required 0.002 to 1 hertz frequency response.

MAGNETIC SELF NOISE TEST

The PMUWS was placed in a triple magnetic shield, powered up, and allowed to warm up for 20 minutes. Also, the sensing element of a Heliflux Model HMS-2 single-axis magnetometer was placed near the center of the PMUWS parallel to the vertical Z axis. The first test revealed that the most sensitive magnetic scale exhibited very low noise other than thermal drift. The thermal drift almost exactly fit a decaying exponential with a time constant of 23.3 minutes and initial amplitude of 61 nT.

The next test was performed after the PMUWS had been left on all night. In this test, the magnetic signals were indeed very stable. The following were the ranges of the magnetic fluctuations during this 28-minute test:

X Axis: 98.1 to 98.5 nT;
Y Axis: 85.2 to 85.8 nT;
Z Axis: 66.5 to 67.3 nT.

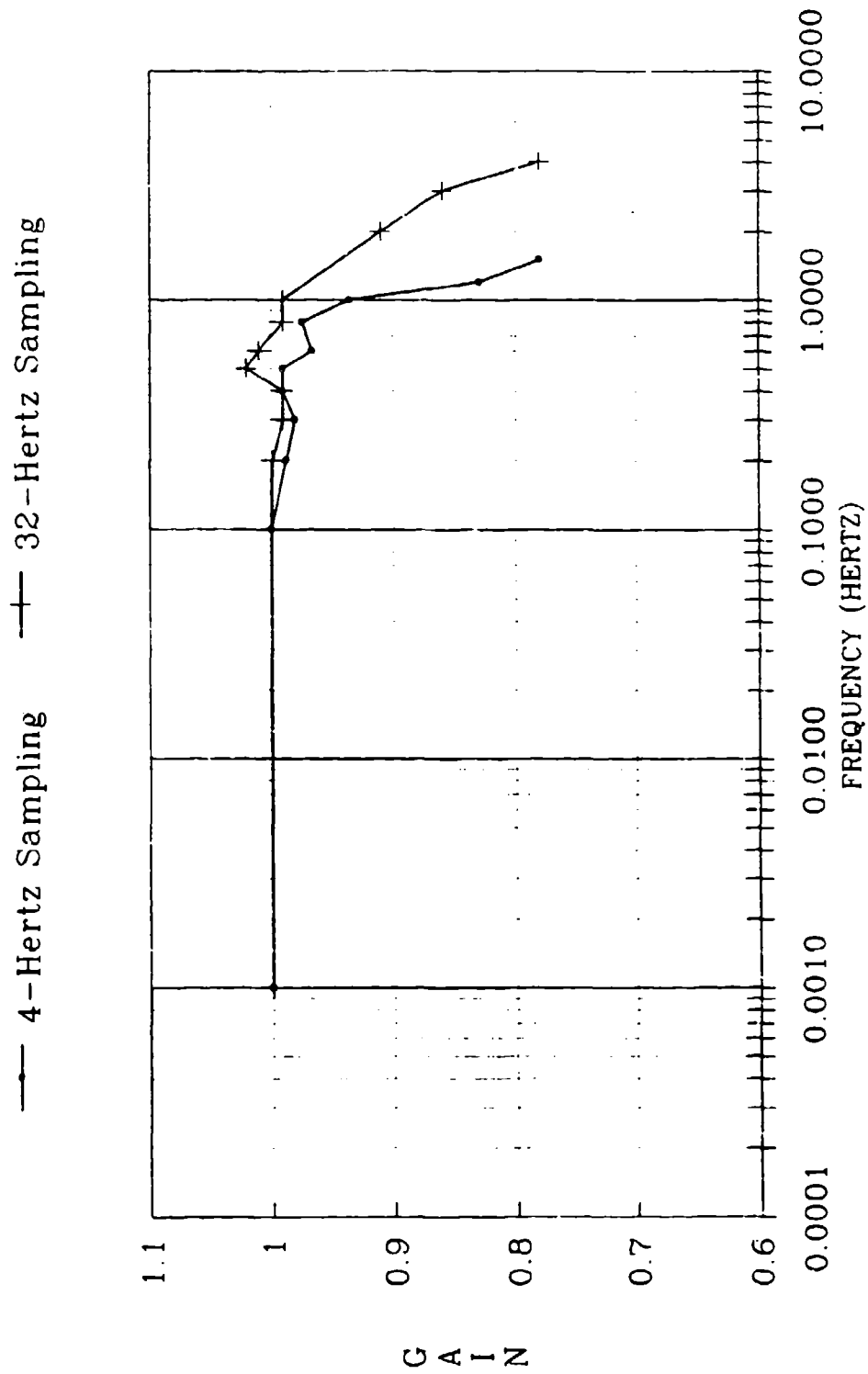


FIGURE 5. PRESSURE CHANNEL FREQUENCY RESPONSE

The changes on the X and Y axes from one sample to the next were never larger than 0.1 nT. On the Z axis, the largest sample to sample change was 0.3 nT. Even these small changes could have been due to the ambient magnetic field penetrating the shield system slightly.

In addition, during the in-water field tests, the magnetic channels of the PMUWS were never observed changing more than 1 least significant bit (0.5 nT) when there was no target in the vicinity.

The tests indicate that the PMUWS magnetic channels have self noise less than the 0.5 nT required in the RFP.

MAGNETIC ORTHOGONALITY

To test the orthogonality of its magnetic axes, the PMUWS was taken to NSWC Building 203 which has a set of three orthogonal, building-size Helmholtz coils. First, a sinusoidal field variation in the PMUWS passband and of 1000 nT 0-p was imposed along the vertical axis; outputs on all three axes were recorded. Next, a sinusoidally-varying magnetic field was applied to the X axis of the PMUWS by aligning the X-axis marker of the PMUWS with the north axis of Building 203 and applying a field to the north axis only; the PMUWS was fine adjusted in orientation for a minimum output on the Y axis. The largest output observed on an off axis was ± 3.5 nT. This corresponds to a nonorthogonality angle of 0.17 degrees, which exceeds the specification by about a factor of 3.

MAGNETIC FREQUENCY RESPONSE

While the PMUWS was in Building 203, the three axes of the PMUWS were tested for frequency response. The applied field was monitored by a Heliflux magnetometer. Figure 6 presents the frequency response plot for the Y axis. The gain curve represents the ratio of the PMUWS magnetic reading to the Heliflux reading. Notice that the curve is very flat at low frequencies, rises to a gain of 1.03 at 0.4 hertz, and then falls off to an amplitude which is at 70 percent of the midband value at 1 hertz. This is correct value for the corner frequency of the three-pole Butterworth filter following the magnetometers. Again, although the range of frequencies was cited the RFP requirements, no limits were put on the gain. Any future RFP should specify limits on gain and gain accuracy.

MAGNETIC RESOLUTION TESTS

On both dynamic magnetic ranges, a small magnetic object was slowly brought close to the magnetic shields with the PMUWS and the magnetic monitor inside. The magnetic monitor was in the X direction. A small fraction of the field from the magnetic object penetrates the shield because the shield attenuation is not total. For both ranges the least significant bits of the X axis of the PMUWS responded when the monitor indicated that amplitudes above the resolution threshold were achieved.

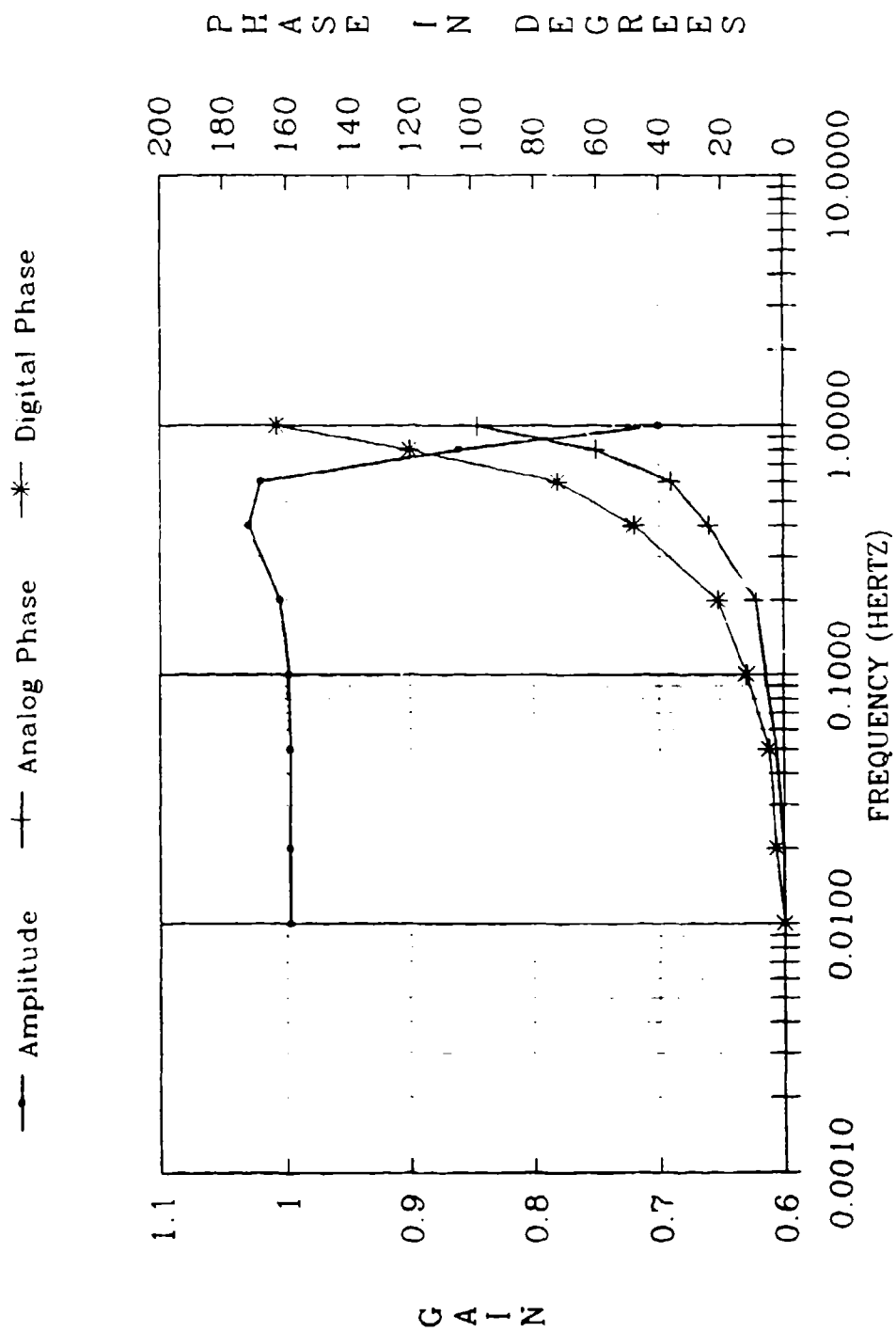


FIGURE 6. Y-AXIS MAGNETIC CHANNEL FREQUENCY RESPONSE

In addition, for both dynamic magnetic ranges, the small magnetic changes induced in the off axes during the 0.01 hertz frequency response test were observed to pass smoothly through successive least significant bit intervals. Thus, the PMUWS was demonstrated to have 0.5 nT resolution on its middle magnetic sensitivity, as required by the RFP. In addition, the most sensitive range, not now formally specified by Dowty, exhibited 0.1 nT resolution.

MAGNETIC DYNAMIC RANGE

With the Helmholtz coils unavailable at the time, it was not possible to generate magnetic fields large enough to overrange the PMUWS magnetometer. To ensure that the dynamic range to the magnetic channels was near the specifications, large magnetic tools were brought near the PMUWS in attempt to push the magnetometer outputs to the limits for all three magnetic sensitivity settings. For the low sensitivity range, the limits of $\pm 100,000$ nT were tested for the +Z and $\pm$ Y directions. For the middle sensitivity, the $\pm 16,384$ nT limits were tested for all but the -Y direction. For the high sensitivity, the $\pm$ limits of ± 3276 nT limits were tested for all but the -X direction.

In all cases tested, it was possible to bring the magnetometer reading to within 0.5 percent of the plus and minus full-scale levels. These test results indicate that at least 99 percent of the potential dynamic range of the PMUWS is actually available for recording before the onset of clipping.

MUTUAL CHANNEL SUSCEPTIBILITY

These tests were added to those described in the test plan to ensure that a large magnetic signature would not induce a objectionable pressure fluctuation and vice versa. The author established the requirements of < 0.01 inch of water variation for a 20,000 nT magnetic variation and < 0.5 nT for a 30 inches of water pressure variation.

The pressure signal was recorded during the previously-mentioned magnetic saturation tests. At no time during magnetic excursions exceeding 50,000 nT on all three axes did the pressure display any variation above 0.01 inch of water correlated with the magnetic waveform.

A sinusoidal pressure variation of 66 inches of water p-p was applied to the PMUWS, and the response of all three magnetic channels on high gain was recorded. None of the three channels showed any response above 0.1 nT correlated with the applied pressure variation.

These tests indicate that the PMUWS meets the requirements for mutual channel susceptibility.

SIGNAL DELAY

Although signal delay was not part of the original RFP requirements, it probably should have been. If the time between the arrival of a physical signal at the PMUWS to the arrival of its digital representation on shore gets too large, the system performance could become unacceptable. A reasonable requirement would be to keep

the delay less than the sum of the delays from: (1) the analog filters preceding the analog to digital converter, (2) one sample period, and (3) 30 milliseconds for sample frame transmission to shore. For example, the PMUWS configured with a 3-pole Butterworth filter with a 1-hertz corner, a 4-hertz sample rate, and a 12-byte sample frame transmitted at 9600 baud, the delay would be about $300 + 250 + 12 = 562$ milliseconds.

After a discussion with U23 personnel about their requirements for signal delays and uncertainties, the most likely format for future recording will be a 4-hertz corner period and an 8-hertz sampling rate, yielding a delay of $75 + 125 + 12 = 212$ milliseconds. This corresponds to a 10-foot longitudinal position error for a 30-knot vessel. It should be possible through a combination of shore computer hardware and software to keep the relative delay of the range house tracking samples to below 100 milliseconds. This will provide 5-foot tracking accuracy for 30-knot vessels, assuming that all other errors are small in comparison.

IN-WATER RECORDING TESTS

In early May, the PMUWS was transported to Fort Monroe for a communications test across the 1-mile underwater, multiconductor cable from the range house to the dock. The PMUWS was powered through the cable. No communication problems were experienced, and the PMUWS appeared to respond normally to coarse pressure and magnetic fluctuations applied to it. The PMUWS was brought back to White Oak for further laboratory testing.

The PMUWS was picked up by U47 personnel in late May 1989 for preparation for an early June plant in the Hampton Roads Channel. U47 personnel had previously made a concrete anchor with three, threaded-steel studs for holding the temperature shield and the PMUWS. Brass brackets were made to hold the PMUWS firmly inside of the temperature shield. The full in-water PMUWS assembly is shown in Figure 7. After the PMUWS was assembled in the temperature shield at the dock, it was given a final functional check from the Range House over the 1-mile underwater cable.

The assembly was planted in the Hampton Roads Channel on 8 June 1989. After the plant, the unit was powered up and recordings were made of the background signal and some untracked targets. Everything functioned well. The next day a U47 L-Boat made several tracked runs and all signals of the PMUWS responded. It was not possible to do full-scale, wild ship ranging on that day because the U47 personnel were previously committed to refurbishing components of their underwater cabling system.

During July and August 1989, the PMUWS participated in 12 wild ship ranging sessions for a total of 100 tracked runs. Figure 8 presents the display from the shore computer for one of those runs. The upper section of the display is a small map of the range laid out in an X-Y grid. The lower section contains the pressure and magnetic signatures along with an icon at the top of the section representing the target's location relative to the signatures. The display is a snapshot of the run when the vessel was 2029 feet past the unit with an athwartship distance of about 38 feet. During the run, the a line representing the track of the vessel was displayed continuously. The slanted line in the upper section is that track.

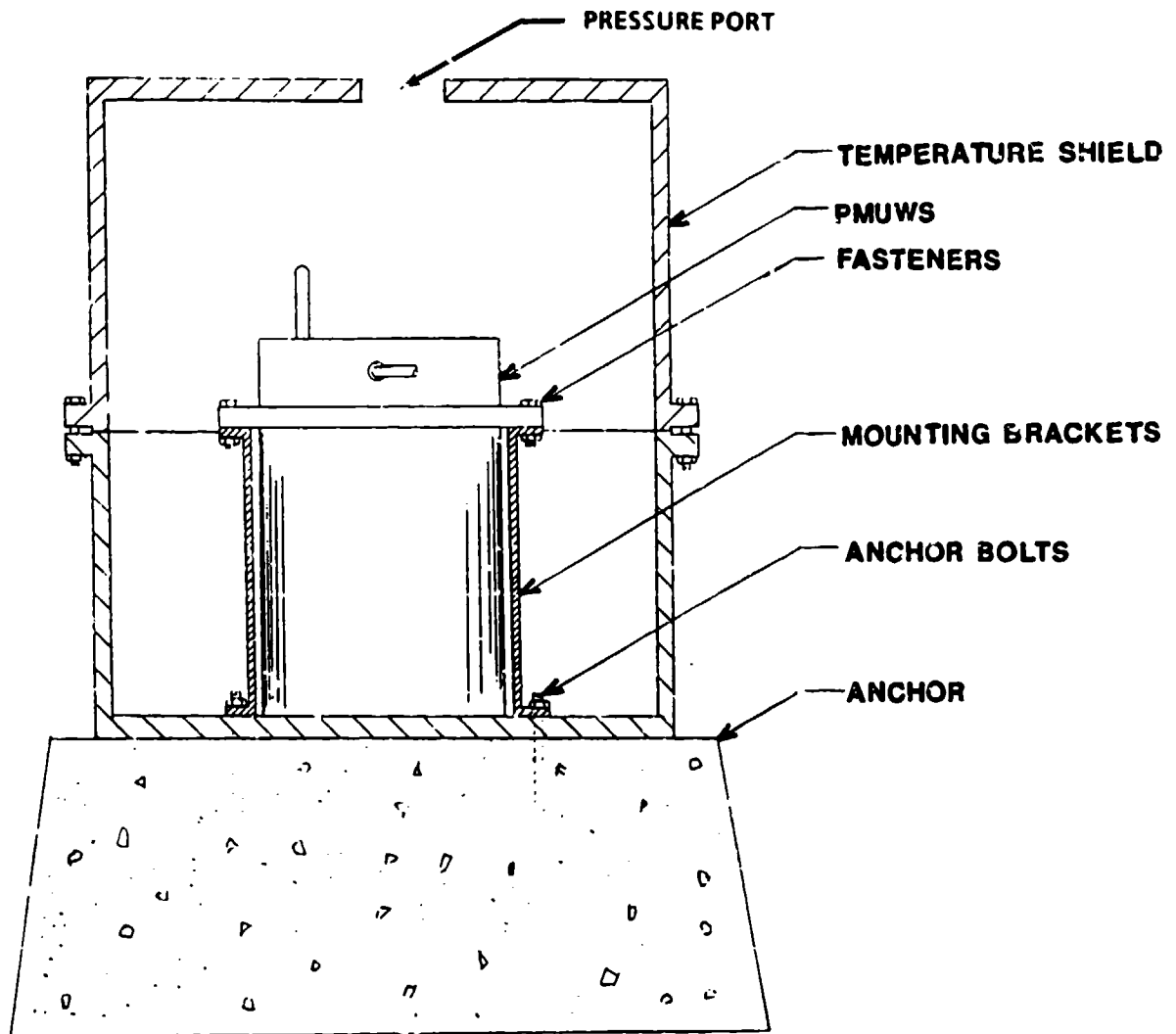


FIGURE 7. PMUWS UNDERWATER ASSEMBLY

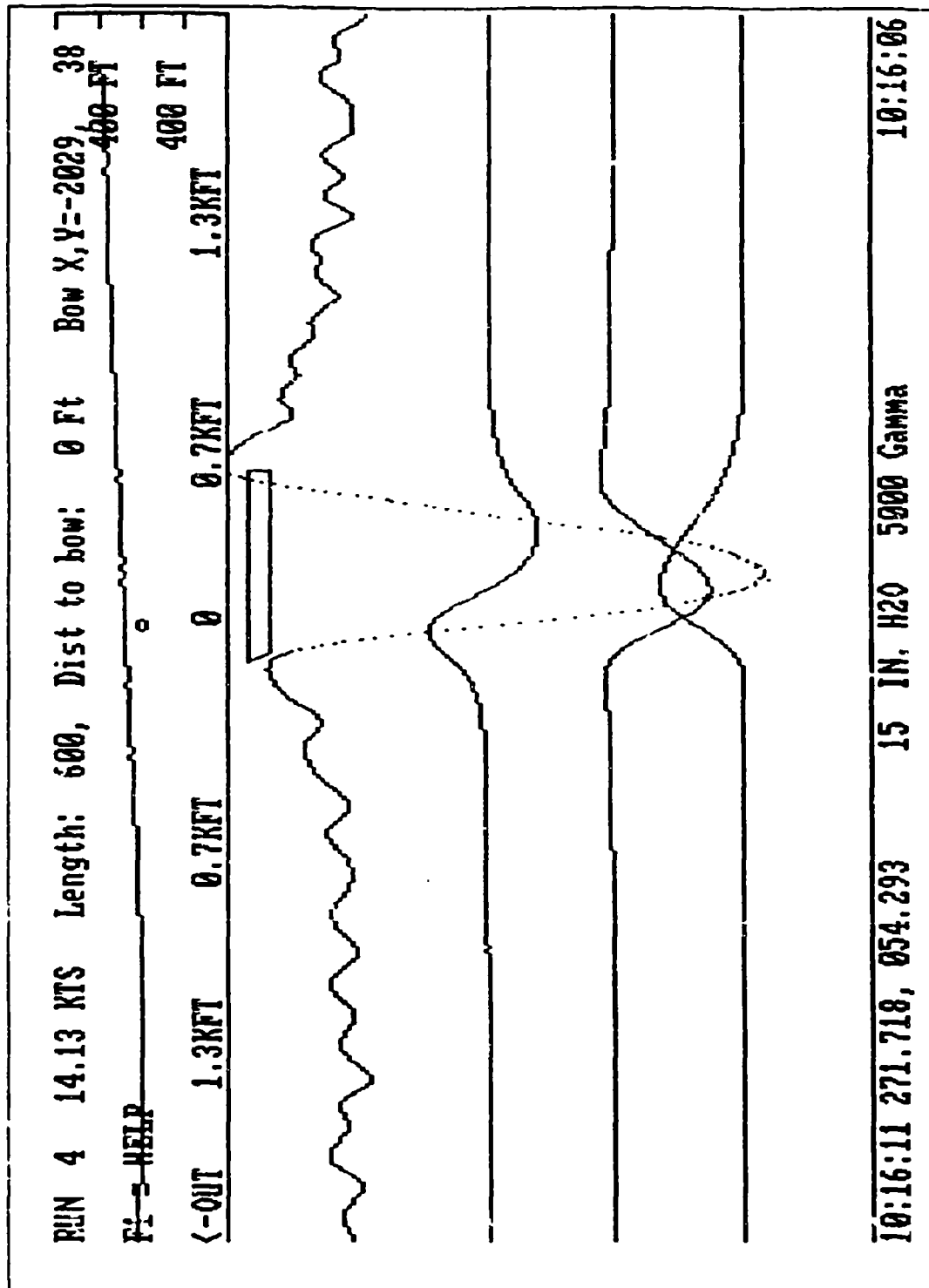


FIGURE 8. SHORE COMPUTER DISPLAY FROM A TYPICAL RUN

The upper curve in the signature section of Figure 8 is the pressure signature, with the characteristic large negative excursion under the vessel. The full scale for the pressure display is 15 inches of water. Below the pressure signature are the magnetic X, Y, and Z signatures in order. The full scale for the magnetic waveforms is 5000 gamma (1 gamma = 1 nT).

There were no irregularities observed in the PMUWS data except for one occasion of repeated data frames at the end of a run on 21 July 1989. Since the target had already passed, this type of problem does not invalidate the data, but it could if it occurred within 15 minutes before a target passage or during a target passage. At this time it is not possible to conclusively prove that the PMUWS was responsible for this problem, since the shore recording system could have caused the problem. If the problem occurs with any regularity in the future, a detailed investigation will be made.

At no time during the ranging sessions did any of the magnetic channels appear to have any low-level noise. Also, most of the time the pressure waveform was smooth, but it was observed that on some days, for periods up to several hours, the PMUWS pressure channel seemed to have noise in the range about 0.01 to 0.1 inches of water. Visual analysis of the noise indicated that the most likely source was real pressure fluctuations due to chop at the surface, in the vicinity of 1 hertz and, thus, was not noise at all. The signal did not have the random character of "popcorn" or "hash" type of noise. As mentioned earlier, to ensure that small pressure fluctuations above 2 hertz do not cause aliasing and to provide the same signal delay for the magnetic and pressure channels, it would be a good idea to require an anti-aliasing filter in the pressure channel that is identical the magnetic anti-aliasing channel.

In general, the PMUWS performed very well during all of the summer ranging sessions.

CORROSION TEST

When the PMUWS was recovered on 23 August 1989, it had been in the Hampton Roads Channel for 76 days. The temperature shield top was removed and the PMUWS was inspected for corrosion. No signs of structural corrosion damage were present on the PMUWS. There were some rust colored stains on some of the stainless steel hardware that holds the PMUWS plastic housing together, but there was no pitting or eroding of the steel. There was no corrosion at all on the pressure sensor.

The worst corrosion observed was on the ends of brass brackets that hold the PMUWS to the concrete anchor. About one-sixteenth of an inch of brass had corroded. It is estimated that this corrosion would take at least 5 years or more to damage the integrity of the brackets. It may be that the combination of steel studs and brass brackets set up an electrochemical reaction. For future plants, a zinc sacrificial anode will be added to see if that holds down the corrosion.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

CONFORMANCE TO REQUIREMENTS

With two exceptions, the PMUWS has been demonstrated to meet the U42 requirements published in the RFP for a pressure/3-axis magnetic underwater sensor package. The first exception is the 0.5-degree manufacturer's specification, cited in their contract proposal, for orthogonality of the three magnetometers. This number is greater than the 0.1 percent requirement. A needs analysis indicated that a level of 0.5 degrees of orthogonality is acceptable. Therefore, the PMUWS was accepted with this specification.

The second exception, discovered during testing, was the sensitivity of the pressure channel to temperature changes. The PMUWS was above this requirement (and the manufacturer's specification) by 25 percent. Given the excellent protection provided by the underwater assembly temperature shield, it was decided that the original requirement of 0.2 inch of water per degree Celsius was unnecessarily strict and that the requirement could be relaxed to 0.5 inch of water per degree Celsius. This would still prevent unacceptable levels of pressure fluctuations due to temperature fluctuations.

In summary, the overall rating of the PMUWS, as currently configured relative to U42 requirements stated in the RFP, is fully acceptable.

NEW REQUIREMENTS FOR NEXT BUY

One of the major outputs of this test program is a set of more comprehensive and refined requirements that reflect both what is economically achievable in underwater magnetic/pressure sensors and what U42 needs. After the lessons learned in this test program, it is proposed that the requirements listed in Table 3 supersede the U42 original sensor package requirements (listed in Table 1) to bring the system into the excellent range relative to U42 needs and to correct deficiencies in the original RFP.

TABLE 3. PROPOSED NEW RFP REQUIREMENTS

1. Three-Axis Magnetometer Requirements:

- a. Triaxial measurement capability.
- b. Minimum static field range of 100,000 nanoteslas.
- c. Minimum dynamic range of $\pm 16,000$ nanoteslas.
- d. Resolution equal to or better than 0.5 nanoteslas.
- e. Sensor self noise and drift less than 1.0 nanoteslas p-p worst case over a 500-second period after a 1-hour warmup with constant ambient magnetic field and temperature.
- f. Loss of orthogonality less than ± 0.5 degrees.
- g. Frequency Response: dc to above 16 hertz.
- h. Accuracy on all ranges should be $< \pm 1$ nT or 1% of reading, whichever is greater.
- i. All three magnetometers provided with self-test coils which provide for self testing of the magnetometers magnetic fields with accuracy of $< \pm 0.5\%$ for a 1000 nT step.
- j. The response of all magnetic channels shall be < 0.5 nT for a 30 inch of pressure change occurring in less than 2 seconds.
- k. The z-axis verticality error must be less than 0.5 degrees for case tilts up to 10 degrees.

2. Pressure Channel Requirements:

- a. Minimum dynamic range of ± 30 inches of water.
- b. Resolution equal to or better than 0.01 inch of water.
- c. Frequency Response: dc to above 10 hertz preferred, 0.002 to 8 hertz acceptable.
- d. Sensor self noise and drift less than 0.05 inch of water p-p worst case over a 500 second period after a 1-hour warmup with constant ambient pressure and temperature.
- e. Temperature sensitivity less than 0.5 inch of water per degree Celsius, including time varying temperatures.
- f. Accuracy on all ranges should be < 0.02 inch of water or 1% of reading, whichever is greater.
- g. The response of the pressure channel must be less than < 0.02 inch of water for a 40,000 nT magnetic step imposed from any direction in less than 2 seconds.

3. Anti-Alias Filtering and Rise Time Requirements:

- a. Anti-aliasing, 3-pole Butterworth filters on all four channels with corner frequency of 4.0 hertz.
- b. Remote selectable corner frequencies at 1.0, 2.0, 4.0, 8.0, and 16.0 hertz for the Butterworth filters mentioned in (1).
- c. The rise of digital signals received from the system to 90 of their final values in response to a step input shall not exceed the rise time of the Butterworth filter plus one sample period plus 30 milliseconds.

TABLE 3. (Cont.)

4. Telemetry Requirements:

- a. It must be possible to control and communicate with the system via an underwater cable from a controlling computer on shore. The cable and computer are user provided.
- b. The sensor sample rate must be settleable to 4, 8, 16, and 32 hertz under control from the remote controlling system.
- c. Electrical connections must be via a single electrical connector, type Crouse-Hinds Male 53F8M-1 requiring a maximum of eight electrical connections.
- d. System must output all samples on a single line or a line pair in a format compatible with a standard serial format such as RS-232, RS-422, or RS-485.
- e. The assembly must be capable of operating when connected to a heavy duty submarine cable up to 10,000 feet long. These cables are coax or 3-, 10-, or 16-conductor twisted lead cables. Typical electrical parameters are 1 ohm/1000 feet, 16 nanofarads/1000 feet, and 80 ohms characteristic impedance.

5. Documentation Requirements

- a. A complete operators manual shall be provided with the system. The manual should provide specifications, high-level design and operating principles, and operating procedures for system checkout, calibration, and operation.
- b. The source code for the software to control the system and communicate with the system shall be provided. This software shall be written in Pascal, BASIC, or FORTRAN for an IBM PC compatible machine.
- c. Disclosure of any software running inside the system is not required, unless knowledge of such software is required to properly operate the system.

6. Electrical, Mechanical and Other Requirements:

- a. Sensors and telemetry electronics must reside in a single waterproof housing.
- b. Housing must be able to withstand water depths up to 200 feet.
- c. No housing dimension can exceed 24 inches.
- d. Total system weight should not exceed 70 pounds.
- e. System must operate on dc voltages not to exceed 100 volts.
- f. Assembly power consumption must not exceed 30 watts.
- g. The sensor assembly must operate within specifications in water up to 100-feet deep.
- h. The system must operate within specification in a temperature range within which -2 degrees to + 30 degrees Celsius after warmup.
- i. All external surfaces should be made of a highly noncorrosive material such as plastic, stainless steel, or titanium.

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 12 December 1989		3. REPORT TYPE AND DATES COVERED Final--1988 to 1989	
4. TITLE AND SUBTITLE PMUWS Acceptance Tests (U)				5. FUNDING NUMBERS NAVSEA-63-89-13A08R1 JO No. 9U15DD25H	
6. AUTHOR(S) Gregory F. Page					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Warfare Center White Oak Laboratory (Code U42) 10901 New Hampshire Avenue Silver Spring, MD 20903-5000				8. PERFORMING ORGANIZATION REPORT NUMBER NSWC TR 89-264	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Commander Naval Sea Systems Command (PMS-407) Washington, DC 20362				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The Pressure Magnetic Underwater System (PMUWS) manufactured by the Dowty Corporation, was tested against the set of requirements listed in the contract used to acquire it. All requirements were met, except for the temperature sensitivity of the pressure channel and the orthogonality of the magnetic axes. It was decided that these requirements could be relaxed while still managing acceptable performance. A more comprehensive and refined set of requirements was developed during this test program for future acquisitions of 3-axis magnetic/pressure underwater instrumentation packages. Test methods and results, along with all requirements old and new, are presented and discussed.					
14. SUBJECT TERMS Pressure Sensors Underwater Instrumentation Magnetic 3-Axis Three-Axis Pressure				15. NUMBER OF PAGES 37	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR		

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