FFI RAPPORT

NATO JRP ELECTRONIC MCM NO PHASE 1 REPORT - SENSOR TECHNOLOGY

SELVÅG Jarle

FFI/RAPPORT-2006/02357

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

REPORT DOCUMENTATION PAGE

1) **PUBL/REPORT NUMBER** FFI/RAPPORT-2006/02357	2) **SECURITY CLASSIFICATION** UNCLASSIFIED	3) **NUMBER OF PAGES** 73
1a) **PROJECT REFERENCE** FFI-IV/896/914	2a) **DECLASSIFICATION/DOWNGRADING SCHEDULE** -	

4) **TITLE**

NATO JRP ELECTRONIC MCM NO PHASE 1 REPORT - SENSOR TECHNOLOGY

5) **NAMES OF AUTHOR(S) IN FULL (surname first)**

SELVÅG Jarle

6) **DISTRIBUTION STATEMENT**

Approved for public release. Distribution unlimited. (Offentlig tilgjengelig)

7) **INDEXING TERMS**

	IN ENGLISH:	**IN NORWEGIAN:**
a)	Measurement	Måling
b)	Measuring instruments	Måleinstrumenter
c)	Ocean Data Acquisitions Systems	Datainnsamlingssystemer for sjø
d)	Sensors	Sensorer
e)	Submerged bodies	Undervannsobjekter

THESAURUS REFERENCE:

8) **ABSTRACT**

This report is the Norwegian contribution in the first phase of the NATO Joint Research Project "03C-3 Mine Models for MCM". It describes modern sensor technologies relevant for the evaluation of a future mine threat scenario. Also contained in the report are examples of state-of-the-art sensors from the commercial market.

9) **DATE** 2006-08-07	**AUTHORIZED BY** This page only Nils Størkersen	**POSITION** Director of Research

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SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

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NATO JRP ELECTRONIC MCM NO PHASE 1 REPORT - SENSOR TECHNOLOGY

1 EXECUTIVE SUMMARY

Although the end of the Cold War has somewhat reduced the need to undertake defensive MCM operations in NATO home ports and bases, a number of geographic areas present serious problems in the near future. In sensitive areas a sophisticated mine threat could present a significant challenge to NATO MCM forces.

The NATO Undersea Research Centre (NURC) initiated in 2004 a Joint Research Project (JRP) named "03C-3 Mine Models for E-MCM". The goal of this project is to deliver a suite of generic mine models that can be utilized in the evaluation of relevant future mine threat scenarios.

The workload of the JRP is divided into five working packages or phases. The first phase is dedicated to the development of a technology trend road map describing state-of-the-art sensor technology relevant for the development of future mines. This report is the Norwegian contribution to the project's first phase.

2 INTRODUCTION

The earliest sea mines were contact mines. Contact mines are still in use, but they have three important disadvantages: They must be anchored to the seabed by a cable that extends nearly to the surface, the radius of action is limited by the target's presented width, and they are most lethal when they detonate significantly below the target, rather than in contact with it. (12)

Modern sea mines are activated by influence. Physical contact with the mine is not required; rather, the presence of a target ship is sensed by monitoring for changes in the ambient underwater environmental field. These changes can be observed in any one of several component influences, including acoustic, pressure, magnetic, electric, seismic and hydrodynamic (flow). Figure 2.1 shows different minefield options available as a function of water depth, including the possibility of a rising mine in deep water.

With increasing complexity of mine warfare technology, the need to establish mine threat software models for safety evaluation purposes has become a priority for the MCM forces. A general mine model should be based on the existing mine threat scenario, as well as an estimation of realistic developments with respect to the future threat. Mine models should thus incorporate realistic sensor characteristics and -topologies, likely signal processing and evaluation possibilities, and mine firing decision logic. Such mine models should also be realistic in the sense that mines with the modelled characteristics are actually producible.

This report will review a selection of the existing sensor technology in the field of magnetic, acoustic, electric, pressure, seismic and hydrodynamic (flow) sensing. The most common measuring principles will be presented along with existing sensor models available on the commercial marked. The listing contained herein is in no way intended to be complete nor is it to be considered representative for a modern mine's sensor suite. The report is aimed at providing some lines of guidance for the assessment of the industrial sensor marked. Unless otherwise stated elsewhere in the report, the presented sensors have not been evaluated with respect to suitability in the mine technology perspective. More, focus has been put on providing a snapshot of the existing sensor marked without making ties to specific influence mine technologies. It has been left to the reader to determine in what direction future mine warfare technology will proceed.

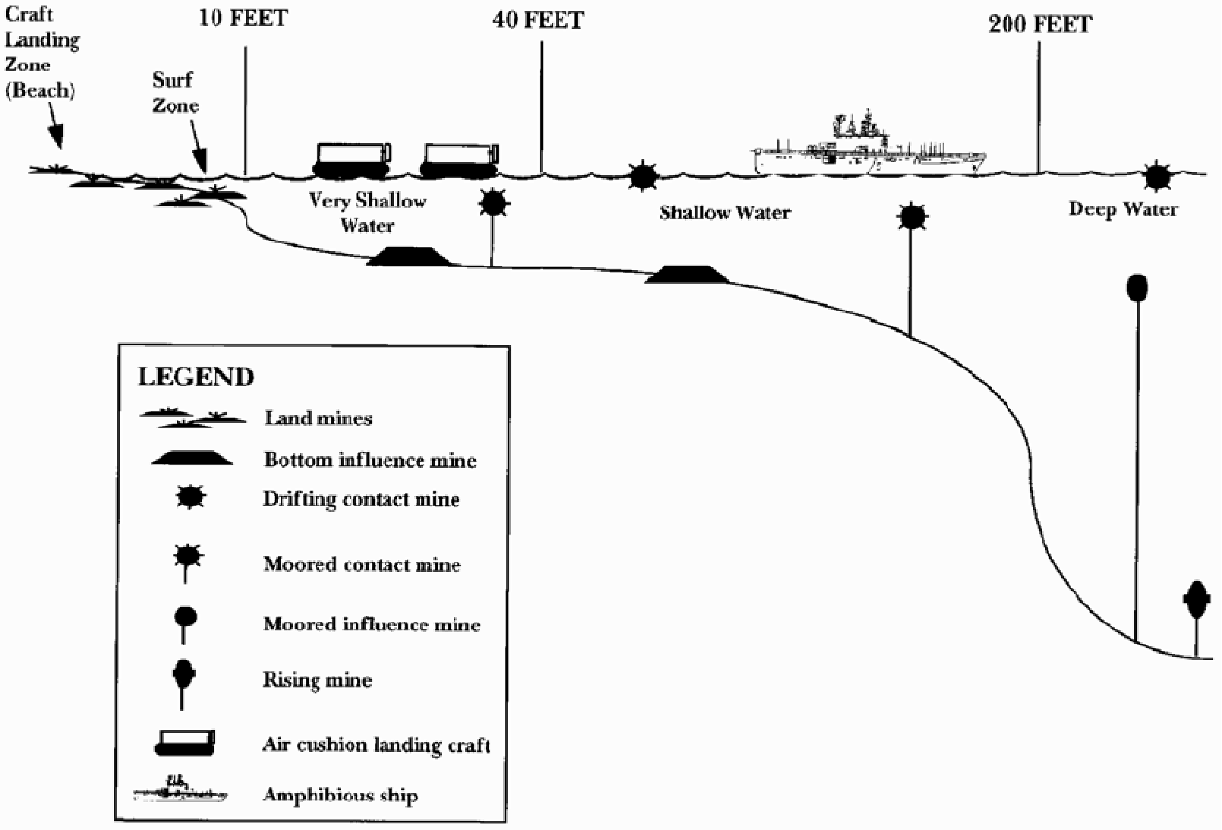


Figure 2.1 Mine warfare strategies as depending on water depth. (12)

3 MAGNETIC FIELD SENSORS

3.1 Introduction

The magnetic signature comprises two components. The permanent magnetisation is a function of the ship's size, material, location and orientation at construction, and can be minimised at that time. The induced magnetisation is, however, dependent on the current geographical position and orientation of the ship in the earth's magnetic field. It can be reduced by passing currents through multiple coils mounted in three orientations and spaced around the ship. In modern naval vessels, these currents can be changed automatically with geographical location and with the heading of the ship. Magnetic signatures are measured by passing the ship over a degaussing range.

The peak magnitude change however is very small in comparison with the natural background field, itself a function of geographical location. The duration is a function of the speed of the ship, but is normally between 1 and 30 seconds. Waves and swells also induce variations that may contaminate the measurement. In addition, much smaller, higher frequency components of less than 0.1 nT may be present, and of importance. Analogous to pressure measurements, the strength of the actual background field at the time is required for accurate data interpretation. (2)

3.2 Physical principle

There is a broad range of technology available for measuring magnetic field strength. Most of the sensor systems are based on the intimate connection between magnetic and electric phenomena. Figure 3.1 show an overview of the most common types of magnetic field sensors. Typically, gauss meters measure strong magnetic fields (above one millitesla) and magnetometers weak fields (below one millitesla). The scalar magnetometers measure the field magnitude, while the vector types measure each field vector component (magnitude and direction).

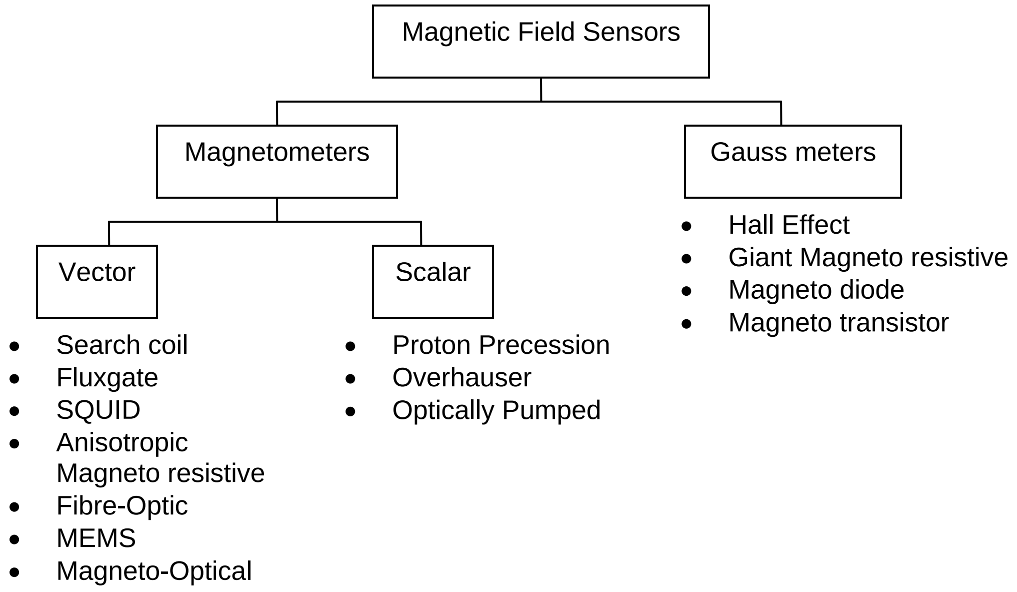


Figure 3.1 An overview of magnetic field sensors. (1)

Induction / search coil:
Induction-coil magnetometers contain a conventional wire coil, often surrounding a permeable core, which measures the time rate of change of magnetic field intensity in a direction parallel to the coil axis (Faraday induction). The sensitivity of each sensor is determined by the effective area and the number of turns of the detection coil and by the magnetic flux density threading the coil. The high-permeability metal core enhances the magnetic flux density.

Induction-coil magnetometers are useful for sensing AC magnetic fields or the relative motion of magnetic objects. Their useful range is typically from 1 Hz to 1 MHz, the upper limit being that set by the ratio of the coil's inductance to its resistance. Performance degrades rapidly at frequencies below 1 Hz, but may approach 10^{-5} nT per square root hertz at frequencies above 1 kHz. Search coils require between 1 and 10 mW of power, all of which is consumed in the readout electronics. (10) (11)

Fluxgate:

Flux-gate magnetometers consist of windings on a ferromagnetic core, the magnetic saturation of which is a function of magnetic-field strength. An applied magnetic field in combination with the drive field produces even harmonics of the drive frequency that are proportional to the strength of the external magnetic field along the core axis. Oriented fluxgate magnetometers have three mutually orthogonal flux-gate sensors that are continuously oriented, so that two of the axes maintain zero field, and the third is oriented parallel to the ambient field direction. Flux-gate sensing elements are typically in the shape of cylinders or rings with lengths or diameter about 2 to 4 cm. Modern three-component fluxgate magnetometers have an operating power of 1.0 W or less. The ability to precisely measure DC and time-varying magnetic fields is a major advantage of flux-gate magnetometers over induction-coil sensors. The upper limit on the frequency is about 10 kHz. The lowest practical noise level is now about 10^{-2} nT per square root Hz at a frequency of 0.1 Hz. The sensitivity range is 10^{-2} to 10^{7} nT. (10)

Superconducting Quantum Interference Device (SQUID):

SQUID magnetometers are the most sensitive of all instruments for measuring a magnetic field at low frequencies (<1 Hz). The SQUID magnetometer is based on the remarkable interactions of electric currents and magnetic fields observed when certain materials are cooled below a superconducting transition temperature. Vector magnetometers employing DC SQUID technology have performances that can exceed 10^{-5} nT. One of the primary obstacles to the use of SQUID magnetic sensing systems is the need for a cryogenic liquid-nitrogen enclosure (at about 80 K or -193 °C). (10) (11)

Hall Effect:

The Hall-effect sensor is a widely used, low cost sensor. An electron moving through a magnetic field experiences a force, known as the Lorentz force, that is perpendicular both to its direction of motion and to the direction of the field. The Hall voltage difference is created as a response to the Lorentz force. The Hall Effect is very small in metallic conductors, but a semiconductor gives a much larger effect. Inexpensive Hall effect sensors are generally made of silicon. Sensors that are more sensitive can be made of the III–V semiconductors, which have higher electron mobilities than silicon. Most commercially available Hall Effect magnetometers have sensing elements made of the III–V semiconductor indium antimonite. The silicon devices have a sensitivity range of 10 to 1000 G or 10^{6} to 10^{8} nT, and the indium antimonite sensors extend the lower limit to 10^{-3} G or 10^{2} nT. Hall Effect sensors can measure either a constant or a varying field; the upper frequency limit is about 1 MHz. They are light and occupy about 0.1 in^2. Their power requirement is between 0.1 and 0.2 W, and they can be operated over an extremely wide temperature range limited only by packaging and lead attachment to the semiconductor. (11)

Magnetoresistive:
MR magnetometers measure the electrical resistance of a material in response to a magnetic field. The magnetic field modulates the scattering of conduction electrons in metals.

The *anisotropic magnetoresistive* effect (AMR) originates from the change in material resistance, which occurs when the magnetisation changes from parallel, with respect to the direction of current flow, to transverse. Some materials, such as perm alloy (an alloy containing about 80% nickel and 20% iron), exhibit anisotropic magnetoresistance. The magnetoresistive sensors have a sensitivity range of to 50 G or to nT with open-loop readout electronics. With closed-loop feedback readout electronic methods, the minimum detectable field can be reduced to 0.1 nT for limited bandwidths. With open-loop readout electronics, these sensors have an extremely wide dynamic range from dc to nearly 1 GHz. These sensors are light, small, require between 0.1 and 0.5 mW of power, and can be operated at temperatures between 55 °C and 200 °C.

The *giant magnetoresistive* (GMR) effect is achieved by using a four-layer structure that consists of two thin ferromagnets separated by a conductor. The fourth layer is an antiferromagnet that is used to pin (inhibit the rotation of) the magnetization of one of the ferromagnetic layers. The ferromagnet layer that is being pinned is between the conductor and the antiferromagnet. This structure is called a spin valve. Electrons can travel more easily either parallel to the layers or perpendicular to the layers if the magnetizations of the two ferromagnets are parallel to one another. When they are aligned, the electrical resistance of the structure is low. When the magnetisations are antiparallel aligned, the resistance is high. The difference in resistivity between the case when the magnetizations are parallel to when they are antiparallel can be as large as 12.8% at room temperature. GMR magnetometers tend to have more 1/f noise than AMR sensors. Present GMR sensors can be used in fields as small as 10 nT at 1 Hz to as large as about 10^8 nT. (10) (11)

Magnetic tunnel junction (MTJ) or *spin dependent tunnelling* (SDT) have a structure similar to the four-layer structure described above in GMR sensors. Again, there are two ferromagnets separated by an intervening layer, but in this case, the intervening layer is an insulator. In MTJ sensors, the conduction occurs by tunnelling of electrons across the insulator. MTJ sensors have higher magnetoresistance values and base impedance than GMR sensors. Because of their higher impedance, MTJ sensors use less power than GMR sensors. These devices often have a high inherent noise, and different noise mechanisms, such as shot noise, dominate at different bias voltages. Because of their high magnetoresistance, high impedance, and planer geometry, MTJ sensors have potential for being used as low cost, energy efficient, high sensitivity magnetic sensors. (11)

Magneto-diode:
A magneto-diode is essentially a semiconductor diode, or *pn* junction. In a magneto-diode, however, the *p* region is separated from the *n* region by an area of undoped silicon. If a metal contact on the *p*-doped region is given a positive potential and a metal contact on the *n*-doped region is given a negative potential, holes in the *p*-type material and electrons in the *n*-type material (the charge carriers) will be injected into the undoped silicon. The current is the sum of the hole-current and the electron-current. A magnetic field perpendicular to the direction of

travel of the charge carriers deflects them either down (increasing resistance) or up (decreasing resistance), depending on the direction of the field. The response of a magneto-diode to a magnetic field is about ten times larger than the response of a silicon Hall-effect device. (11)

Magneto-transistor:
This sensor, like the magneto-diode, is an integrated silicon device. If the magneto-diode is a version of a *pn*-junction, the magneto-transistor is a version of an *npn*-transistor. Like the transistor, it consists of an *n*-doped emitter separated from an *n*-doped collector by a *p*-doped base. The difference is that there are two collectors instead of one. In the absence of a magnetic field, equal numbers of charge carriers arrive at both collectors. If there is a magnetic field perpendicular to the direction of travel of the charge carriers, they are deflected toward one collector or the other, depending on the direction of the field. The two-collector voltages are fed to a difference amplifier, whose output is proportional to the applied magnetic field. Two different effects are used in magneto-transistors to detect magnetic fields. These are the Hall and Suhl effects. In the Hall Effect, the Lorentz force is compensated by an opposing electric field, which is sensed between the two collectors. The Suhl effect takes place when the Lorentz force is not compensated. An external magnetic field causes a change in trajectory of the moving carriers, resulting in a variation in the current distributions that is detected between the collector outputs. Although both effects occur simultaneously, it is possible to design devices in which one effect is dominant. The magneto-transistor is expected to be 100 times more sensitive than the silicon Hall-effect device and is based on a standard fabrication technology (i.e., silicon substrates). (11)

Fibre-optic (magnetostrictive):
Fibre-optic magnetometers measures magnetic fields by exploiting the difference in optical path length between an optical fibre that is mounted on a magnetostrictive material and an unclad fibre-optic cable. The sensor operates in a frequency range from DC to 60 kHz. The sensor size depends on the sensitivity required. Fibre-optic magnetometers and fibre-optic intrinsic magnetic gradiometers are used to implement unobtrusive and remotely operable magnetic intrusion sensors for military and civilian secure-facility protection and for detection of the presence of metal objects such as weapons near designated security zones. The fibre-optic magnetometer has a sensitivity range of to 10 G or to nT. It can be employed to sense either constant fields or fields fluctuating with frequencies below 60 kHz. A typical sensor is roughly four inch long and one inch wide. (10) (11)

Magneto-optical:
The magneto-optical sensor exploits the Faraday Effect, which involves the rotation of the plane of polarization when light travels through a magnetic material. The effect is largest in a few crystals when the propagation directions of the light, the crystal axis, and the applied magnetic field are all aligned. It is possible to construct lab top magneto-optical magnetometers with a sensitivity of 30 pT. The unique advantage that the magneto-optical sensor has over other magnetic sensors is its very fast response time. Sensors with gigahertz response have been fabricated. (11)

Micro-electromechanical systems (MEMS):

Many of the earliest designs of magnetic sensors utilized simple magnetic attraction to ferrous objects. The resulting motion was then measured to record or detect metal objects. A structure similar to a compass needle was the first magnetic field triggered fuse for mines. With the development of micro-electromechanical systems (MEMS), the idea of using movement to sense magnetic fields is being re-examined.

Most of the MEMS sensors utilize the Lorentz force. For example, a magnetometer can be based on detecting the motion of a miniature bar magnet. The bar magnetic responds to the field without drawing any power. Fields as small as 200 nT can then be detected optically. The field cab also be determined by measuring the feedback required to maintain a constant tunnelling current. A resolution of 0.3 nT/√Hz at 1 Hz can thus be achieved. Here, the sensitivity is limited by air pressure fluctuations. An alternative approach uses a xylophone resonator. In this approach, an AC current whose frequency is adjusted to be equal to the resonant frequency f_0 of a MEMS beam is sent through the length of the beam. A DC field applied perpendicular to the axis of the beam will energize motion of the beam at the frequency f_0. The amplitude of the motion, that can be detected optically, is proportional to the field.

MEMS technology can improve magnetic sensors by minimizing the effect of 1/f noise. This is accomplished by utilizing a MEMS flux concentrator, in which the flux concentrators, composed of soft magnetic material, are placed on MEMS flaps. The flux concentrators enhance the field, and by decreasing the separation between the flaps, the enhancement is increased. The two MEMS flaps are forced to oscillate by applying an AC voltage to the electrostatic comb drives. By tuning the frequency, one can excite the normal mode in which the distance between the flaps oscillates. The resonant frequency for the MEMS structure is designed to be about 10 kHz. The oscillation of the MEMS flaps modulates the field at the position of the sensor and, hence, shifts the operating frequency of the sensor above the frequency where 1/f noise dominates. Depending on the type of magnetic sensor used, this shift in operating frequency should increase the sensitivity of magnetometers by one to three orders of magnitude. (11)

Electron resonance / optically pumped:

These magnetometers use the shift in the frequency of electron resonance to measure external magnetic fields. In general, resonance devices measure only the amplitude (modulus) of the external vector field and are relatively insensitive to orientation. For this reason, they are often favoured for use on moving platforms. (10)

Electron resonance magnetometers are also called electron paramagnetic resonance (EPR), optically pumped or quantum magnetometers. They work on the principle of optically monitoring the absorption and re-radiation of electron energy levels of atoms in the gaseous state. According to the Zeeman Effect, an external field can split electron energy levels into sublevels. The energy difference between the sublevels corresponds to a radio frequency according to Planck’s Law, and it is proportional to the external magnetic field. If radio-frequency energy is introduced by means of a coil, at the proper frequency, transitions can be induced between the sublevels. This population change in substates results in the optical pump doing some work to restore equilibrium. By noting the frequency at which absorption of the pump beam occurs, we can determine the amplitude of the external magnetic field. Alkali elements, such as He-4, potassium, rubidium, or cesium are commonly used in optically pumped magnetometers. (In an Earth field of 50,000 nT, a potassium magnetometer would operate at a radio-frequency resonance of 350 KHz, while a helium magnetometer would operate at 1.4 MHz.) Electron resonance magnetometers have achieved noise levels of 10^{-3} nT per root Hz at a frequency of 0.1 Hz. The narrow-line potassium magnetometer seems to have the greatest potential for low-noise operation; under laboratory conditions it has been operated at a noise level of 10^{-5} nT (0.01 picotesla). Because of their relatively high resonance frequencies, electron resonance magnetometers are much less affected by rotation-rate errors than nuclear resonance devices. This, coupled with their intrinsic relative insensitivity to orientation, makes them good candidates for operation on moving platforms. For various reasons, electron resonance magnetometers are relatively power hungry, most requiring 10 W or more. At present, these sensors are also limited by the cost and size of the glass containers holding the alkali gas. There are efforts to build glass ampoules into silicon chips, but the fabrication process is nontrivial. (10) (11)

Nuclear resonance / precession:

These magnetometers use the shift in the frequency of nuclear resonance to measure external magnetic fields. In general, resonance devices measure only the amplitude (modulus) of the external vector field and are relatively insensitive to orientation. For this reason, they are often favoured for use on moving platforms. (10)

Magnetometers that use nuclear resonance are commonly known as nuclear-precession- or NMR magnetometers. They exploit the response to a magnetic field of the nuclear moments of atoms in a hydrocarbon fluid such as benzene. Principal NMR devices are the proton-precession magnetometer, the Overhauser proton magnetometer, and the He-3 magnetometer. In all three devices, the nuclear magnetic moments are first polarized and then allowed to precess around the external field vector. The precession frequencies are atomic standards proportional to the amplitude of the external field. The precession frequency is picked up by coils and counted to obtain a measure of field amplitude. Field measurements are normally obtained no more often than every 2.0 seconds. Practical proton-precession magnetometer noise levels are about 10–1 nT per root Hertz at a frequency of 0.1 Hz. Typical average power consumption is 2.0 W or more at maximum cycle rates. Their frequency range is limited by the gating frequency of the hydrocarbon fluid. (10) (11)

In the Overhauser proton magnetometer, the protons are polarized by a radio frequency “pump” (approximately 80 MHz) acting through a buffer solution. This device can be operated continuously, unlike the proton-precession magnetometer. Practical noise levels of Overhauser magnetometers are 10^{-2} nT per root Hz at frequencies of 0.1 Hz and 1.0 Hz and 10^{-2} nT per root Hz at frequencies of 0.1 Hz and 1.0 Hz. Power consumption can be 1.0 W or less. In the He-3 magnetometer, polarization is achieved by an optical pump. It can be operated continuously and has potential for low noise (10^{-3} nT per root Hz at a frequency of 0.1 Hz). This magnetometer can be operated at power levels of 0.5 W or lower. Because of their low resonance frequencies, NMR magnetometers have large rotation-rate errors; thus, they should be stabilized when operated on a moving platform. (10)

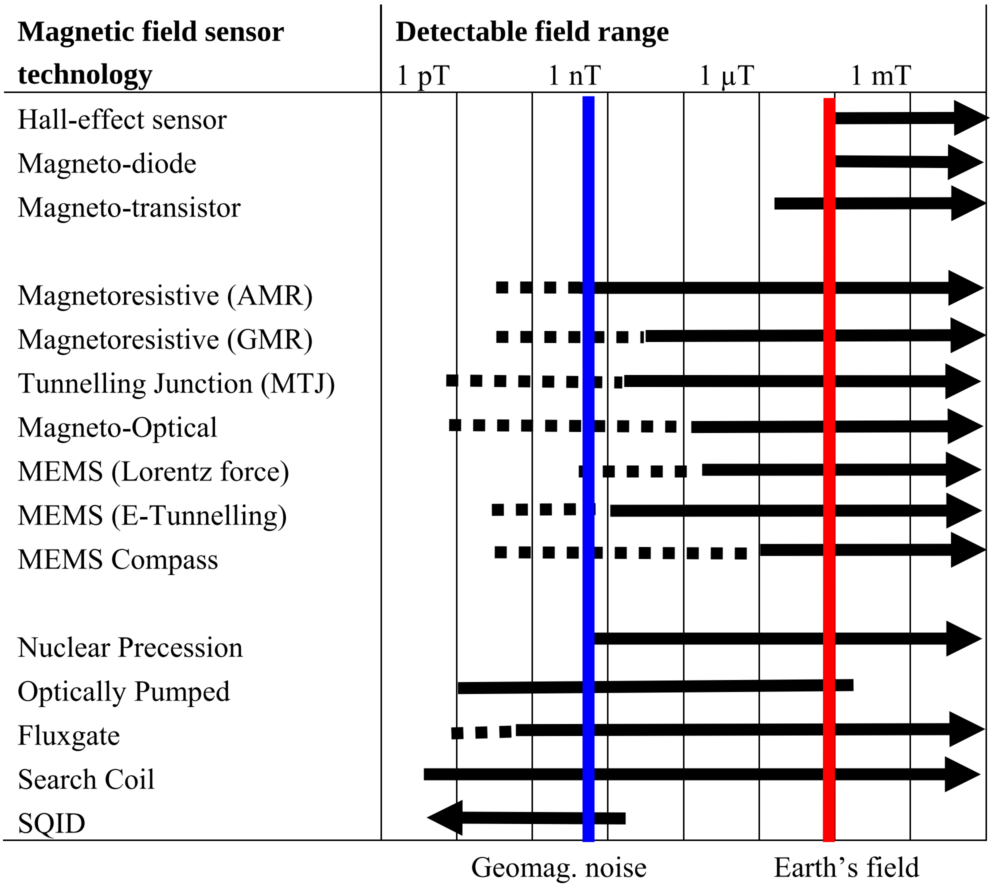


Table 3.1 Magnetic Sensor Technology and Field Ranges. (11)

3.3 Sensor examples

3.3.1 Bartington Instruments

Bartington Instruments provides custom-designed single and three-axis fluxgate magnetometers and gradiometers optimised for low power, internal noise, radiated noise, bandwidth, cost, size or other parameters where sufficient quantities are required. Applications include pipe and cable location, magnetic surveillance, MRI, defence and aerospace. Board-level products are available for OEM customers.

Mag-03 series:
These compact, high performance sensors with integral electronics provide precision measurements of static and alternating magnetic fields in three axes. They are available with measuring ranges of ±70, ±100, ±250, ±500 or ±1000µT in a range of enclosures as detailed below. Powered from any ±12V supply, outputs are in the form of three analogue voltages from 0 to ±10V, proportional to B_x, B_y and B_z. Low noise sensors with a noise level of <6pTrms/√Hz at 1Hz can be supplied in all enclosures with a measuring range of ±70 or ±100µT. The Mag-03 sensors can be supplied in the following enclosures:

- Mag-03MC - cylindrical
- Mag-03MCES - cylindrical - with environmentally sealed connector
- Mag-03MCFL - cylindrical - with connections via flying leads
- Mag-03MS - square section

- Mag-03MSES - square section with environmentally sealed connector
- Mag-03MSS - square section submersible to 100 metres
- Mag-03IE - a sensor with the three sensing elements on flying leads.

Mag-03MRN:

The Mag-03MRN is designed to meet the requirements of NASA for attitude control of upper atmosphere research vehicles and contains three orthogonal sensors with integral electronics for the measurement of static and alternating magnetic fields in three axes. The unit operates from a power source of 24 to 34V and provides three outputs of 0 to +5V proportional to the field in each axis. A 2.5V bias monitor output is provided. The magnetometer is available as the Mag-03MRN60 with a range for each axis of ±600 mG (±60μT) or the Mag-03MRN45 with a range of ±450 mG (±45μT). The magnetometer has a brass case with a grey painted finish. The fixing points are reinforced with internal brass bushes. The use of screened connecting cables is recommended for optimum results.

Mag-566V:

This miniature magnetometer comprises a single board assembly with fluxgate sensors and electronic circuitry. The unit is optimized for low power operation whilst providing low noise and superior temperature stability. The unpackaged design is suitable for incorporation into vehicle and industrial plant movement monitoring. The low drift characteristics also allow the magnetometer to be used as a terrestrial field monitor or as an orientation sensor.

The Mag566V magnetometer has a full-scale range of ±100μT. It operates from a ±5V supply and provides three analogue outputs of zero to ±4.5V with a bandwidth of 0 to 35Hz. The 20mW power consumption and low self-noise make this magnetometer an excellent choice for battery-powered applications. A digital input can be activated to apply a known magnetic field to each axis to test for correct functioning. No latch-up or phase reversal occurs outside the normal range.

A current boost circuit ensures rapid settling of the sensor outputs when power is applied. The electronics is encapsulated in polyurethane to provide a high level of environmental protection. The lightweight construction allows the magnetometer to be used in applications where it may be subjected to high levels of shock and vibration.

Mag-03MS

Mag-03MRN

Mag566V

Figure 3.2 Fluxgate magnetometers from Bartington Instruments.

Mag-03MS:

Supply voltage	±12V to ±17V
Analogue output	±10V (±12V supply) swings to within 2V of supply voltage
Power supply rejection ratio	5µV/V
Output impedance	<1 ohms
Linearity error	<0.0015%
Calibration accuracy	±0.5%
Bandwidth	0 to 3 kHz
Orthogonality error	Between sensing axes: <0.1° Z axis to reference face: <0.1°
Internal noise	Standard version: <12pTrms/√Hz at 1Hz Low noise version: <6pTrms/√Hz at 1Hz
Supply current	Standard version: +25mA, -8mA (+1.4mA per 100µT for each axis) Low noise version: +30mA, -8mA (+1.4mA per 100µT for each axis)
Enclosure	Reinforced epoxy
Dimensions	32 x 33 x 152mm
Mounting	2 x M5 fixing holes
Operating temperature range	-40°C to +70°C
Weight	160g
Environmental	IP61
EMI	Zero RF emission

Measuring range	±70	±100	±250	±500	±1000	µT
Scaling	143	100	40	20	10	mV/µT
Offset error	±5	±5	±12	±25	±50	nT
Scaling temperature coefficient	+15	+20	+50	+100	+200	ppm/°C
Offset temperature coefficient	±0.1	±0.1	±0.2	±0.33	±0.6	nT/°C

Mag-03MRN:

Magnetic field range	±600 milligauss (±60µT) for Mag-03MRN60 ±450 milligauss (±45µT) for Mag-03MRN45
Zero field output	2.5V ±50mV from 0°C to 60°C
Sensitivity	2.5V ±50mV per 600 milligauss (60µT) at 26°C for Mag-03MRN60 2.5V ±50mV per 450 milligauss (45µT) at 26°C for Mag-03MRN45
Orthogonality	±1° maximum error per axis relative to the case reference surface
Crosstalk	25mV maximum for 600 milligauss (60µT) orthogonal field
Linearity	±25mV maximum deviation from best straight line, established by a least squares fit, over the full magnetic field range.
Temperature stability	
Zero field output	±50mV maximum variation from 0°C to 60°C
Sensitivity	±3% maximum variation from 0°C to 60°C
Phase response	2° maximum phase lag between input crossover and output from 0 to 20Hz

Frequency response	2% maximum variation in output from 0 to 20Hz
Output impedance	100 ohms
Output noise and ripple	25mV peak to peak maximum
Input voltage range	24 to 34VDC (60V absolute maximum) Will withstand surges up to 45V for 30 seconds Protected against reverse polarity of applied power
Output voltage range	+6VDC to -1VDC absolute maximum
Supply input current	25mA normal operation 50mA with output short circuit
Case material	Brass with part grey epoxy powder coat finish, part gold flash
Dimensions	1.25 x 1.34 x 4.75 inches including connector
Mounting	two through holes for 4-40 screws drilled 0.120 inch (No. 31) with 11/16 inch gap between centres
Weight	6.5 ounces
Random vibration	20 "G" RMS from 20Hz to 2000Hz for 20 seconds in three axes
Steady state acceleration	+60 "G" for 1 minute in three axes
Operating temperature range	-10°C to +70°C (within specification from 27°C to 60°C)
Storage temperature range	-40° to +85°C

Mag-566V:

Range	±100µT
Calibration accuracy	≤ ±3%
Orthogonality error	≤ ±2°
Linearity error	≤50ppm
Hysteresis at full scale	≤50ppm
Internal noise	Standard deviation of 1.5nT maximum, 0.75nT typical over a 30 second time period in the bandwidth 0.1 to 30Hz
Output scale factor	±4.5V /±100µT [45µV/nT]
Temperature coefficient of scale factor	+50ppm/°C (±10%)
Zero field offset error	±500nT max
Temperature coefficient of offset error	±0.2nT/°C
Bandwidth (-3dB)	30 to 40 Hz
Output impedance	100Ω, short circuit protected, drives capacitive loads up to 1µF
Test response, 0V on Test input	-110nT (±10%)
Internal clock frequency	5-6kHz
Breakthrough of internal clock at output	<10mV p-p max* (1.5mV p-p typical)
Perming	10nT max/mT external field
Dimensions (mm)	20H x 42W x 52D (±0.5)

Weight	27g
Mounting	4 x 3.2 internal diameter chromated aluminium pillars on 40mm x 30mm fixing centres
Protection	Resin encapsulation
Operating temperature range	-32°C to +50°C
Storage temperature	-40°C to +70°C
Supply voltage	±4.8V to ±5.2V (±5.5V absolute maximum)
Supply current	±2 (±0.4)mA quiescent, plus a maximum of 1.5mA/100µT external field Automatic boost at switch-on: ±7-9mA (Allow 20s for full stability)
Power supply rejection ratio	1nT/50mV

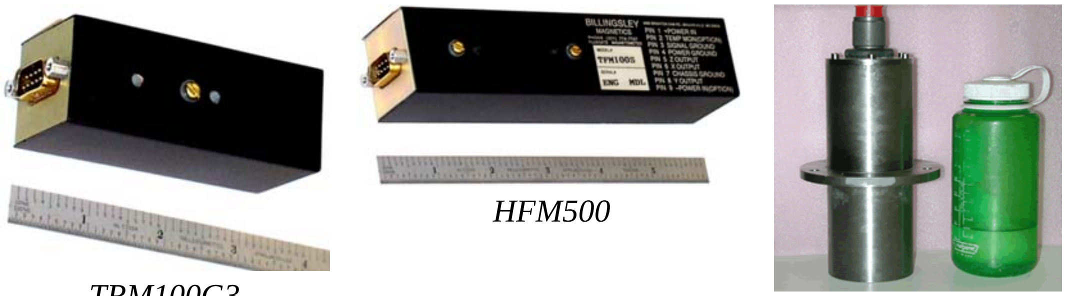
3.3.2 Billingsley Aerospace & Defence

Billingsley Aerospace manufactures fluxgate magnetometers for spacecraft attitude control, military and commercial applications.

TRM100G3:
The TRM100G3 is an ultra-miniature tri-axial fluxgate magnetometer intended for spacecraft attitude control and general magnetic measurements in laboratory or field applications such as remotely piloted vehicles, data buoys, sounding rockets, etc. To increase reliability, the instrument has been designed without fuses, potentiometers and switches.

DFM24G:
The DFM24G is a low noise / high-resolution magnetometer with very low power consumption. It is ideal for magnetic surveys, general laboratory use and underwater degaussing range applications. All functions, both digital and analogue, are mounted on a single miniature printed circuit board and installed in a lightweight housing with remote tri-axial sensor head or in an integral underwater housing as required by user. The DFM24G is designed for the highest reliability and for long term unattended use in applications such as underwater ranges, where retrieval and or repair would be cost prohibitive.

HFM500:
This is a miniature tri-axial fluxgate magnetometer intended for measurement of large magnetic fields, and can be configured to measure fields up to ± 15 Gauss.



TRM100G3

HFM500

HFM500 titanium

Figure 3.3 Fluxgate magnetometers from Billingsley Aerospace & Defence.

TRM100G3:
Axial alignment: Orthogonality better than ± 1°.
Input voltage options: 20 to 34 VDC at ≤ 550mW constant power.
Field measurement range options: ± 60mT = ± 9.6V.
Accuracy: ± 0.75% of full scale (0.5% typical).
Linearity: ± 0.01% of full scale.
Sensitivity: 160 µV/nT.
Scale factor temperature shift: ≤ 0.002% full scale/ °C.
Noise: ≤ 12 picoTesla RMS/ √Hz @1 Hz (≤ 8 pT option).
Output ripple: ≤ 3 millivolt peak to peak at 2nd harmonic.
Analogue output at zero field: ± 0.025 Volt.
Zero shift with temperature: ≤ 1.0 nT/°C.
Susceptibility to perming: ± 8 nT shift with ± 5 Gauss applied.
Output impedance: 332 Ω ± 5%.
Frequency response: 3 dB at > 500 Hz (to > 3 KHz wideband).
Over load recovery: ± 5 Gauss slew < 2 milliseconds.
Random vibration: > 20G RMS, 20 Hz to 2 KHz.
Temperature range: - 40° to + 85°C operating.
Acceleration: > 60G.
Weight; size: 150 grams; 3.66 cm x 3.58 cm x 15.44 cm.

DFM24G:
Axial alignment: Orthogonality better than ± 0.1° (0.02 ° special).
Input voltage: 16 to 34 VDC at 750 mW constant power ideal for battery powered operation.
Field measurement range: ± 65 mT standard (other ranges on request).
Scaling accuracy: ± .03 % of full scale.
Digital linearity: ± .001 % of full scale.
Scale factor temperature shift: ≤ .002 % / °C typical.
Noise: ≤ 10 pT Rms/√Hz @ 1Hz (special), < 20 pT standard.
Zero offset: ≤ 5 nT.
Susceptibility to perming: < ± 5 nT shift with ± 5 Gauss applied.

Data interface: RS232C or RS485 serial interface. Can drive cable lengths >1000 meter.
Conversion speed: 25 µs per sample.

Digital output resolution: 24 bits at 4096 sample averaging, 22 ½ bits with 128 samples averaged. 22 ½ bits = 20 picoTesla resolution.

Size of electronics card: Single card 15.24 Cm x 4.13 Cm, can be packaged in many user defined housings. All analogue and digital functions contained on a single miniature electronics card.

HFM500:
Axial alignment: Orthogonality better than ± 1°.
Input voltage: 18 to 35 VDC.
Input current: 28 mA at zero field +1.5 mA/Gauss/axis.
Feedback ripple current: 5 mA peak to peak.
Field measurement range: ± 500,000 nT (other ranges available).
Accuracy: ± 0.75% of full scale (0.5% typical).
Linearity: ± .007% of full scale.
Sensitivity: 20 µV/nT.
Scale factor temperature shift: 0.01% full scale/ °C.
Noise: ≤ 20 pT RMS/√Hz at 1 Hz.
Output ripple: 3 mV peak to peak at 2nd harmonic.
Analogue output at zero field: ± 0.020 V.
Zero shift with temperature: < 1 nT / °C.
Susceptibility to perming: ± 8 nT shift with ± 5 Gauss, ± 30 nT shift with ± 15 Gauss.
Output impedance: 332 Ω ± 5%.
Output load: Unconditionally stable with any load capacitance; will drive any length cable.
Frequency response: -3 dB at > 1 kHz; available with > 4 kHz with increased output ripple.
Random vibration: 20G RMS 20 Hz to 2 kHz.
Temperature range: - 40° to + 85°C operating.
Acceleration: 60G.
Weight; size: 182 grams; 3.51 cm x 3.51 cm x 15.37 cm.
Chassis: Aluminium with ground jumper option to select optimum EMI shielding.

3.3.3 Honeywell International

The advantages of Honeywell's magnetic sensor components are their small size, high accuracy and solid-state design. Honeywell's magnetic sensors are designed to accurately detect the direction and magnitude of external magnetic fields for compassing and magnetometry applications. From discrete sensors for OEM applications, to high performance solid-state compasses and magnetometers, Honeywell magnetic sensor products operate on nearly any platform.

HMC1053:
The Honeywell HMC1051, HMC1052 and HMC1053 are magnetoresistive sensors designed for low field magnetic sensing. Various packaging options have been created from the basic HMC1052 sensor chip to create 1, 2 and 3-axis magnetoresistive sensors for cost effective and small size solutions. The advantage of the HMC105X family of sensors is in the near-perfectly orthogonal dual sensor on a single chip with shared set/reset and offset coils/straps included.

The HMC105X family utilizes Honeywell’s Anisotropic Magnetoresistive (AMR) technology that provides advantages over coil based magnetic sensors. They are extremely sensitive, low field, solid-state magnetic sensors designed to measure direction and magnitude of Earth’s magnetic fields, from 120 micro-gauss to 6 gauss. Honeywell’s Magnetic Sensors are among the most sensitive and reliable low-field sensors in the industry. Applications for the HMC105X family of sensors include low cost Compassing, Magnetometry, and Current Sensing.

HMC2003:

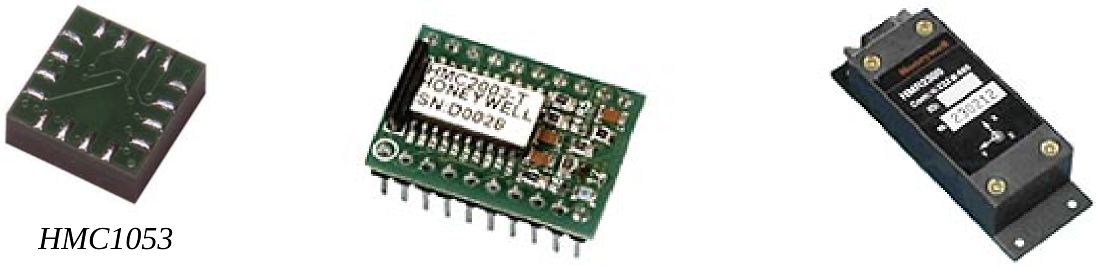
- 20-pin wide DIP Footprint (1” by 0.75”).
- Precision 3-axis capability.
- Factory calibrated analogue outputs.
- 40 micro-gauss to ±2 gauss dynamic range.
- Analogue output at 1 Volt/gauss (2.5V @ 0 gauss).
- Onboard +2.5 volt reference.
- +6 to +15 volt DC single supply operation.
- Very low magnetic material content.
- -40° to 85°C operating temperature range.

The Honeywell HMC2003 is a high sensitivity, three-axis magnetic sensor hybrid assembly used to measure low magnetic field strengths. Honeywell’s most sensitive magneto-resistive sensors (HMC1001 and HMC1002) are utilized to provide the reliability and precision of this magnetometer design. The HMC2003 interface is all analogue with critical nodes brought out to the pin interfaces for maximum user flexibility. The internal excitation current source and selected gain and offset resistors, reduces temperature errors plus gain and offset drift. Three precision low-noise instrumentation amplifiers with 1 kHz low pass filters provide accurate measurements while rejecting unwanted noise.

HMR2300:

- High accuracy over ±1 gauss, <0.5% full scale.
- Range of ±2 gauss, <70 μgauss resolution.
- Three axis (X, Y, Z) digital outputs.
- 10 to 154 samples per second, selectable.
- RS-232 or RS-485 serial data interfaces.
- PCB or aluminium enclosure options.
- 6-15 volt DC unregulated power supply interface.

The Honeywell HMR2300 is a three-axis smart digital magnetometer to detect the strength and direction of an incident magnetic field. The three of Honeywell’s magneto-resistive sensors are oriented in orthogonal directions to measure the X, Y and Z vector components of a magnetic field. These sensor outputs are converted to 16-bit digital values using an internal delta-sigma A/D converter. An onboard EEPROM stores the magnetometer’s configuration for consistent operation. The data output is serial full-duplex RS-232 or half-duplex RS-485 with 9600 or 19,200 data rates. A RS-232 development kit version is available that includes a windows compatible demo program, interface cable, AC adapter, and carrying case.



HMC1053

HMC2003

HMR2300

Figure 3.4 AMR magnetometers from Honeywell.

HMC1053:
Supply: Min 1.8, typical 3, max 20 volts.
Resistance (bridge current = 10mA): Min 800, typical 1000, max 1500 ohms.
Operating temperature: -40 to +125 °C.
Storage temperature: -55 to +150 °C.
Humidity (tested at 85°C): 85 %.
Field range full scale (FS): -6 to +6 gauss.
Linearity error (best fit straight line):
± 1 gauss: 0.1 %FS
± 3 gauss: 0.5 %FS.
± 6 gauss: 1.8 %FS.
Hysteresis error (3 sweeps across ±3 gauss): 0.06 %FS.
Repeatability error (3 sweeps across ±3 gauss): 0.1 %FS.
Sensitivity (set/reset current = 0.5A): Min 0.8, typical 1.0, max 1.2 mV/V/gauss.
Noise density @ 1kHz (V_{bridge}=5V): 50 nV/sqrt Hz.
Resolution (50Hz Bandwidth, V_{bridge}=5V): 120 µgauss.
Bandwidth, magnetic signal (lower limit = DC): 5 MHz.

HMC2003:
Sensitivity: Min 0.98, typical 1, max 1.02 V/gauss.
Null field output: min 2.3, typical 2.5, max 2.7 V.
Resolution: 40 µgauss.
Field range (maximum magnetic flux density): -2 to 2 gauss.
Output voltage (each magnetometer axis output): 0.5 to 4.5 V.
Bandwidth: 1 kHz.

Linearity error:
±1 gauss Applied Field Sweep: Typical 0.5, max 2 %FS.
±2 gauss Applied Field Sweep: Typical 1, max 2 %FS.
Hysteresis error (3 Sweeps across ±2 gauss): Typical 0.05, max 0.1 %FS.
Repeatability error (3 Sweeps across ±2 gauss): Typical 0.05, max 0.1 %FS.
Power supply effect (power varied from 6 to 15V with ±1 gauss applied field sweep): 0.1 %FS.

Temperature:
Operating: -40 to +85 °C.
Storage: -55 to +125 °C.
Shock: 100 g.
Vibration: 2.2 g rms.

Supply Voltage: 6 to 15 VDC.
Supply current: 20 mA.

HMR2300:
Supply Voltage: 6.5 to 15 Volts.
Supply Current (V_{supply} = 15V, with S/R = On): Typical 27, max 35 mA.

Operating (ambient): -40 to +85 °C.
Storage (ambient, unbiased): -55 to 125 °C.

Range (full scale (FS), total field applied): -2 to +2 gauss.
Resolution (applied field to change output): Min 67 micro-gauss.
Accuracy (RSS of all errors @+25°C):
± 1 gauss: Typical 0.01, max 0.52 %FS.
± 2 gauss: Typical 1, max 2 %FS.
Linearity error (best fit straight line @+25°C):
± 1 gauss: Typical 0.1, max 0.5 %FS.
± 2 gauss: Typical 1, max 2 %FS.
Hysteresis error (3 Sweeps Across ± 2 gauss @+25°C): Typical 0.01, max 0.02 %FS.
Repeatability error (3 Sweeps Across ± 2 gauss @+25°C): Typical 0.05, max 0.10 %FS.
Gain error (applied field for zero reading): Typical 0.05, max 0.10 %FS.
Offset error (applied field for zero reading): Typical 0.01, max 0.03 %FS.

Weight:
PCB only: 28 grams.
PCB and non-flanged enclosure: 94 grams.
PCB and flanged enclosure: 98 grams.
Vibration (operating):
5 to 10Hz for 2 Hours: 10 mm.
10Hz to 2kHz for 30 Minutes: 2.0 g.

3.3.4 Marine Magnetics Corporation

SeaSPY Marine Magnetometer:

- SeaSPY is an entirely omnidirectional Overhauser magnetometer.
- It has the highest absolute accuracy of any magnetometer: 0.2nT
- The repeatability between SeaSPY sensors is also unmatched at better than 0.01nT.
- It delivers high-resolution output with a noise level of 0.01nT/√Hz; counter sensitivity is 0.001nT

- It is entirely maintenance free and most importantly, SeaSPY's specifications do not degrade over time.
- It only requires 1W standby and 3W maximum. SeaSPY can run for days directly from a 24V vehicle battery.
- SeaSPY is digital. The magnetometer signal is measured inside the towfish where the signal is strongest and most resistant to outside noise.
- Do not require temperature stabilization.
- No temperature effect on accuracy: Data collected at –40ºC will be identical to data recorded at +60ºC
- No heading error: Heading error is a detectable offset in the magnetometer output caused by changing the heading of the magnetometer within the Earth's magnetic field.
- Marine Magnetics' SeaSPY magnetometer is constructed of the most nonmagnetic materials possible.

Explorer Mini Marine Magnetometer:

- Weighs 3 kg (7 lbs), 50m (164ft) of cable weighs 6 kg (13 lbs).
- Explorer Overhauser sensors are entirely maintenance free and most importantly, Explorer's specifications do not degrade over time.
- Explorer's maximum power consumption is only 2W. A 24V Universal AC power supply is supplied with each system. Explorer can also be powered by a single car battery.
- Explorer is entirely omnidirectional, meaning you never have to orient your sensor, because it is already optimized to work around the World.
- Explorer is digital. The magnetometer signal is measured inside the tow fish where the signal is strongest and more resistant to outside noise.
- Explorer Overhauser sensors deliver high-resolution output with a noise level of 0.02nT/√Hz; counter sensitivity is 0.001nT. In other words, Explorer is orders of magnitude more sensitive than proton sensors, and is on par with optically pumped sensors.
- Explorer, like Marine Magnetics' SeaSPY marine magnetometer, has the best absolute accuracy of any marine magnetometer available: 0.2nT
- Explorer Overhauser sensors do not require temperature stabilization.

Sentinel Base Station Magnetometer:

Sentinel is a complete self-contained long-term magnetic monitoring station. It contains a battery pack and a low-power omnidirectional Overhauser magnetometer all sealed in a pressurized housing. Sentinel's sensitivity is state-of-the-art (0.015nT), far superior to most traditional base station magnetometers, and its power requirement is orders of magnitude lower. Sentinel is built with premium materials that are designed to withstand years of exposure to the harshest environments. The main housing is high strength fibreglass coated with impact-absorbing polyurethane similar to the SeaSPY towed magnetometer system.

Magnum Borehole Magnetometer Probe:

- The Magnum probe achieves an absolute accuracy of 0.2nT regardless of any external conditions such as temperature, or relative orientation of the ambient magnetic field.
- An extremely low noise spectrum of 0.02nT/√Hz RMS (wideband) places the Magnum probe among the most sensitive magnetic field measurement instruments available.

- A Magnum probe will produce valid data regardless of its orientation relative to the Earth's magnetic field.
- Magnum's Overhauser technology produces high signal levels from a very small sensor volume. At 51mm diameter (pressurized), the Magnum probe is the smallest commercially available total field magnetometer.
- Magnum's Overhauser technology is power efficient, requiring only 3W for the entire unit, including telemetry. This allows the Magnum probe to be used easily with very long cables, and allows the use of smaller, lighter field batteries.
- Magnum uses magnetically clean metal fittings, and a high strength, high-toughness fibreglass pressure housing for the ultimate in corrosion immunity. All internal components are well cushioned, making the unit very tolerant to impacts and mechanical stress.

SeaSPY Marine

Explorer Mini Marine

Sentinel Base Station

Magnum Borehole Probe

Figure 3.5 Overhauser magnetometers from Marine Magnetics Corporation.

SeaSPY Marine Magnetometer:

Absolute accuracy: 0.2nT.
Sensor sensitivity: 0.01nT.
Counter sensitivity: 0.001nT.
Resolution: 0.001nT.
Dead zone: NONE.
Heading error: NONE.
Temperature drift: NONE.
Power consumption: 1W standby, 3W maximum.
Time base stability: 1ppm, -45ºC to +60ºC.
Range: 18,000nT to 120,000nT.
Gradient tolerance: Over 10,000nT/m.
Sampling range: 4Hz – 0.1Hz.
External trigger: By RS-232.
Communications: RS-232, 9600bps.
Power supply: 15VDC-35VDC or 100-240VAC.
Operating temperature: -45ºC to +60ºC.
Temperature sensor: -45ºC to +60ºC, 0.1 step.
Tow fish length: 124 cm (49 inches).
Tow fish diameter: 12.7 cm (5 inches).
Tow fish weight in air: 16 kg (35 lbs).
Tow fish weight in water: 2 kg (4.4 lbs).

Explorer Mini Marine Magnetometer:
Same specifications as for SeaSPY, except for:
Sensor sensitivity: 0.02nT.
Power consumption: 2 W.
Power Supply: 9VDC - 40VDC or 100 - 240VAC.
Tow fish length: 86 cm (33.75 inches).
Tow fish diameter: 6 cm (2.375 inches).
Tow fish weight in air: 3 kg (7 lbs).
Tow fish weight in water: 1.2 kg (2.6 lbs).

Sentinel Base Station Magnetometer:
Sensitivity: 0.015 nT.
Resolution: 0.001 nT.
Gradient tolerance: > 10,000 nT/m.
Range: 18,000 to 120,000 nT.
External trigger: by RS-232.
Absolute accuracy: 0.2 nT.
Temperature drift: NONE.
Dead zone: NONE.
Heading error: NONE.
Sampling rates: 1/Minute to 1Hz.
Communications: RS-232, 9600bps.
Magnetometer cylinder weight: 14kgs.
Magnetometer cylinder size: 113cm x 13cm dia.
Docking base weight: 5kg.
Magnetometer cylinder depth rating, with brass seal installed: 1000m.
Operating temperature: -25C to +60C.
Storage temperature: -60C to +70C.
Storage capacity: one million readings.
Battery pack: Gel cell 12V, 7Ah.
Battery charge time: 5 hours 80% charge. 10 hours full charge. Can charge while sampling.
Power consumption:
    Sample rate 1Hz: 960mW (80 hours per battery charge).
    Sample rate 0.3Hz: 700mW (110 hours per battery charge).
    Sample rate 0.2Hz: 490mW (155 hours per battery charge).
    Sample rate 0.1Hz: 150mW (540 hours per battery charge).
    A sample once per minute: 25mW (>2500 hours per battery charge).

Magnum Borehole Magnetometer Probe:
Diameter: 51mm (2.0 inches).
Length: 85cm (33.6 inches).
Weight: 2.5kg (5.5lb).
Operating temperature: -40°C to +60°C.
Pressure rating: 50bar (725psi, 500m of water).
Power requirement: 15-35VDC, 3W maximum.

Sensitivity (noise spectral density): 0.02nT/√Hz RMS.
Resolution: 0.001nT.
Absolute accuracy: 0.2nT.
Repeatability between sensors: < 0.01nT.
Gradient tolerance: 5,000 nT/m.
Operating range: 20,000nT to 120,000nT (worldwide).
Temperature drift: None (<0.01nT/100°C).
Heading error: None (<0.01nT).
Orientation restrictions: None.
Sampling rate: 0.1Hz to 4Hz user-selectable.

3.3.5 Wuntronic GmbH

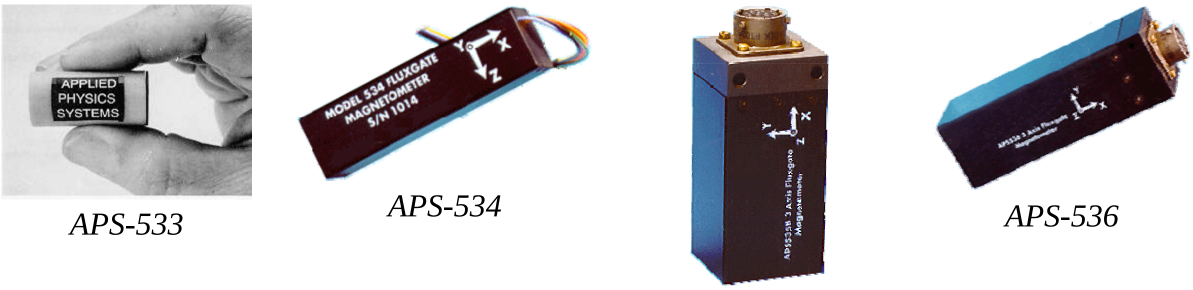
Model APS-533:
The APS533 System is a complete 3-axis Fluxgate Magnetometer packaged in a cylindrical fibreglass package diameter 0.725" (18.415 mm) and length 1.5" (38.1 mm). The system operates from input voltage of ±5 VDC and consumes a total power of 200 mW. Connection to the system is accomplished by means of six #22-gauge Teflon insulated wires with a normal length of 6" (152.4 mm).

Model APS-534:
The APS534 system is a complete 3-axis fluxgate magnetometer packaged in a rectangular/parallelepiped package of dimensions 0.75" (18mm) x 0.75" (18mm) x 2.75" (70mm). The package corners are rounded to enable the unit to fit inside a 1.0" diameter cylinder. The system operates from input voltages of ±5 VDC and consumes a total power of 300 mW.

Model APS-535:
The model 535 magnetometer is a complete 3-Axis Fluxgate Magnetometer system packaged in a rectangular package of dimensions 1.5"x1.5"x3". With low noise and relatively small size, the instrument can be used wherever relatively small magnetic fields (.02 milligauss to 5 Gauss) need to be measured. Full-scale output is ±10 volts, which represents a magnetic field of ±5 Gauss. The system is simple to operate and set up.

The 535 system employs an optional active failure recognition system to detect when any of the three fluxgate-sensors stops working properly. The failure system functions by applying a low-level magnetic signal to each fluxgate sensor and then detecting the presence of the signal in each of the fluxgate output channels. A “failure” logic output signal is provided to alert the user should any of the fluxgate-sensors stop working.

Model APS-536:
The model 536 magnetometer is a complete 3 Axis Fluxgate Magnetometer system packaged in a rectangular package of dimensions 1.5"x1.5"x4.65". With low noise and small size, the instrument can be used wherever small magnetic fields (3 x 10-7 to 1 Gauss) need to be measured. Output from the sensor is 3 analogue voltages proportional to the magnetic field in three orthogonal directions. Full-scale output is ±10 volts, which represents a magnetic field of ±1 Gauss. The system is simple to set up and operate.



APS-533 *APS-534* *APS-535* *APS-536*

Figure 3.6 Fluxgate magnetometers from Wuntronic GmbH.

Model APS-533:
Range: Selectable ± 1 G, ± 2 G or ± 10 Gauss.
Noise level: < 1x10-6 G RMS/root Hz.
Frequency response: DC to 400 Hz (-3 db).
Linearity: ±0.02% of full scale.
Zero output temperature coefficient (0°C to 70°C): < ±2 x 10-5 G/°C.
Scale factor temperature coefficient (0°C to 70°C): < ±0.02% full scale/°C.
Sensitivity: ±4 V/G.
Orthogonality between axes: ±2°.
Alignment of sensor package with sensor reference surfaces: ±2°.
Size (cylindrical): 0.725" (18.415 mm) diameter x 1.5" (38.1 mm) length.
Weight: 18 grams.
Power input: +5 VDC at 20 mA, -5 VDC at 20 mA.
Input connections: Six #24 gauge insulated wires 6" (152.4 mm) long.

Model APS-534:
Range: Up to 1 Gauss.
Noise level: <1x10-6 G RMS/root Hz.
Frequency response: DC to 400 Hz (-3 db).
Linearity: ±0.1% of full scale.
Drift in zero with temperature: < ±0.002 V.
Drift in scale factor with temperature: < ±2 x 10-5 G/°C.
Sensitivity: ±4 V/G.
Orthogonality between axes: ±2°.
Alignment of sensor package with sensor reference surfaces: ±0.2°.
Size (cylindrical/rectangular parallelepiped):
0.75" (18 mm) x 0.75" (18 mm) x 2.75" (70 mm) long (with fit inside 1" diam. tube).
Weight: 30 grams.

Power input: +5 VDC at 20 mA, -5 VDC at -20 mA.
Input connections: Six #26 gauge insulated wires 4" (102 mm) long.

Model APS-535:
Sensitivity: 2V/Gauss (at ± 10 G then 1 V/Gauss).
Dynamic range: ±5 Gauss (± 10 G available).
Linearity: ±0.5%.
Orthogonality and alignment: ±1° with reference surface.
Noise level: <.02 milligauss rms @ 1 Hz½.
Frequency response: DC to 400 Hz (-3 db).
Active fitness monitor tone: 0.05 Gauss @ 1000 Hz.
Fitness monitor output: TTL high for OK, low at failure.
Power requirement: ±15V.
Power consumption: +55 ma @ 15V, -43 ma @ -15V.
Size (excluding connector): 1.5"x1.5"x3".
Connector: 10 pin Bendix.

Model APS-536:
Sensitivity: 10V/Gauss (at ± 10 G then 1 V/G).
Dynamic range: ±1 Gauss (± 10 G available).
Linearity: ±0.2%.
Orthogonality and alignment: ±0.2° with reference surface.
Noise level: <3 x 10-7 G rms Hz½.
Frequency response: DC to 400 Hz (-3 db).
Power requirement: ±15V.
Power consumption: +60 ma @ 15V, -60 ma @ -15V.
Size (excluding connector): 1.5"x1.5"x4.65".
Connector: 10 pin Bendix.

3.4 Recommendation

Fluxgate and search-coil sensors are still the most likely devices of choice for ship signature assessment. They are more sensitive than magneto-resistive, magnetostrictive and semiconductor devices, even though some AMR and MEMS sensors come close in performance. In addition, these magnetometers do not require cryogenic cooling as the SQUID sensors do.

Optically pumped magnetometers have high sensivity. Unfortunately, they are inflicted with degraded performance in some directions called “dead zones”. They are also large, expensive, and their power consumption is high (several watts). Of the total field magnetometers, the Overhauser is probably the best choice. These sensors are an order of magnitude more sensitive than nuclear precession magnetometers, and have no “dead zones” like the electron resonance instruments.

4 ELECTRIC FIELD SENSORS

4.1 Introduction

A ship’s electric signature arises from the modulation, by the it’s rotating machinery, of the small currents generated by the immersion of dissimilar metals, such as the steel hull and bronze propellers, in an electrolyte, namely salt water. Active cathodic protection techniques also contribute to the electric signature. Moreover, the forced motion of conductive seawater across the earth’s magnetic field, such as that created by the water displacement and wake turbulence of a passing ship, can create additional electromagnetic disturbances. The composite electric field strengths can be extremely low, in the order of -190 dBV/√Hz/m. However, an electric field sensor must be capable of handling signals more than 90 dB greater. (2)

4.2 Physical principle

In practice, it is inconvenient to try to detect an electric signature by measuring the absolute electrical potential. Instead, the electrical gradient (change in potential) in the water volume near the sensor is measured. A typical sensor thus utilizes two electrodes, mounted 0.2 – 1 meter apart, for each spatial coordinate x, y and z. By measuring the potential difference between each pair of electrodes, the electric field magnitude and the direction of the source can be found. This potential difference must be amplified before any subsequent signal analysis can take place. Since very low voltage levels are to be detected, conventional amplifiers cannot be used due to their self-induced noise, which effectively masks signals of interest. In addition, the use of more than one electrode pair requires galvanic insulation. Therefore, electrodes and amplifiers with unique properties for these applications must be used.

A common choice of material for electrodes, are silver chloride (Ag/AgCl). The silver chloride electrode has a constant potential (0.197 Volts at 0° C) relative to a saturated hydrogen electrode, and presents the possibility to measure slow changes in electric potential. This electrode has been on the marked for a long time and is a result of military research and development. Besides being used in military applications, it is utilized in oceanography and medicine. A drawback is that the silver chloride electrode is expended during use.

Another popular electrode material is carbon. Each electrode is made of a large number of carbon fibres. The total area of carbon exposed to seawater can thus be as large as four square-meters. This ensures good electrical connection between the electrode and the seawater. The carbon fibre bundle is in one end connected to an electrical conductor inside of a waterproof housing. A tube of fibre tissue covers the whole electrode and serves as a mechanical protection for the carbon fibres. This housing also reduces flow-noise from the water and limits biological growth. The carbon fibre sensor is not salinity sensitive and not expended during use. It is usable down to one mHz in frequency because of its behaviour like a capacitor that neutralizes DC voltages. The carbon fibre electrode has a constant potential in the range 0.23 – 0.6 volts. (3)

4.3 Sensor examples

4.3.1 Polyamp AB

- Carbon fibre electrodes - Robust technology
- Very low noise amplifiers - High sensitivity
- Salinity independent - Useable for all waters instantaneously
- Inert sensors - Maintenance free without need for salt bridges
- High reliability - Long life expectancy
- 3 axis platform designs - Fixed and transportable ranges


Amplifier PA3002 *3-axial sensor system* *3-axial sensor system*

Figure 4.1 Electric field sensor systems from Polyamp AB, Sweden.

PA3002: Low noise galvanically insulated amplifier with selectable gain for use with low resistive UEP sensors.

Frequency band:	
AC mode:	0.005 - 1100 Hz (with gain of 80dB).
DC mode:	0 - 1100 Hz (with gain of 70.6 dB).

Power consumption:	1.3 W.
Supply voltage:	+/- 15V.
Input noise (self induced noise):	20nV/√Hz at 5mHz. 0.7nV/√Hz at 1000Hz.
Max range:	+/- 3mV/m.
Total dynamics:	160 dB.

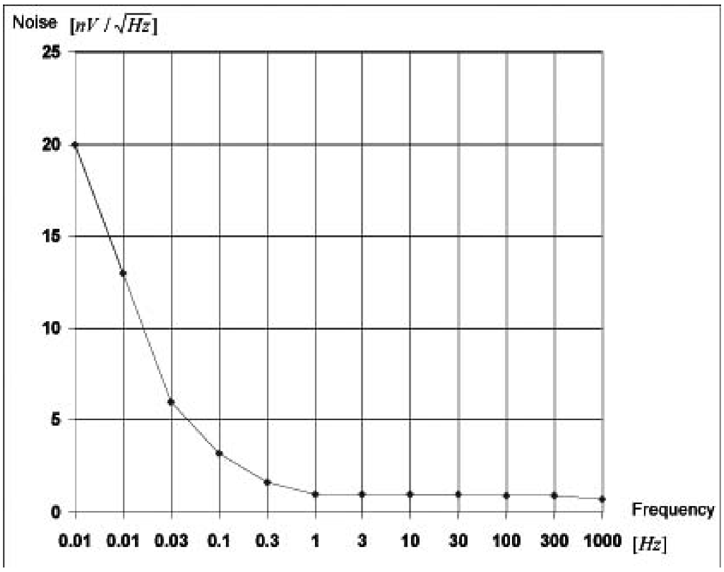


Figure 4.2 Typical noise frequency plot on the PA3002 electronics module.

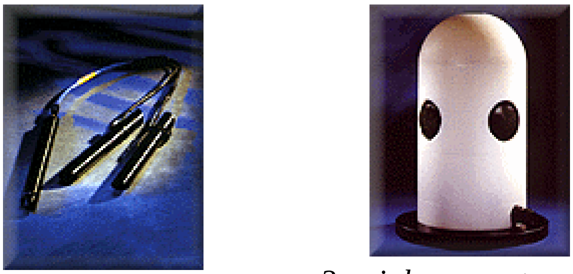
4.3.2 Subspection Limited

Miniature sensor:

- Battery operated with low power consumption.
- Stand-alone instrument that is easily integrated with other sensors in a multi-influence package.
- Individual sensors can be combined to form a multi-axis system.
- Low noise electrodes combined with high quality pre-amplifier ensure a balanced and integrated system.
- Surface mount electronics enables miniaturization of sensor design.
- Low weight enables suspension of sensor from a buoy or helicopter.
- Ideally suited for use as a picket or for surveillance.

Compact sensor:

- Three axis sensor combining sensing electrodes and electronics in a single underwater unit.
- Compact design enables its addition to existing magnetic and acoustic measurement ranges enhancing their multi-influence capability.
- Versatile, stand-alone instrument that can be easily combined with other sensors in a multi-influence system.
- Low noise electrodes combined with it's high performance pre-amplifiers, ensure a balanced, integrated system.
- Electric fields of a few nanovolts per meter are readily detected.
- Lightweight sensor and can be easily deployed.



Miniature sensor, one axis   *3-axial compact sensor*

Figure 4.3   Electric field sensor systems from Subspection Ltd, UK.

Miniature sensor:

Measurement Axes:	Single Axis	Diameter Electrode Housing:	25mm
Frequency Range:	1mHz to 1KHz	Length Electrode housing:	225mm
Dynamic Range:	±10mV/m max.	Diameter Amplifier Housing:	25mm
System Noise Level:	Supplied on request	Length Amplifier Housing:	225mm
Voltage Supply:	±6V	Weight in air:	880g
Current Drain:	<±1mA	Electrode Spacing (Nominal):	20m

Compact sensor:

Measurement Axes:	3 Orthogonal (X, Y, Z)	Height:	500mm
Frequency Range:	5mHz to 1KHz	Sensor Diameter:	250mm
LF band:	5mHz to 5Hz	Base Diameter:	350mm
HF band:	1Hz to 1KHz	Weight in air:	28Kg
Dynamic Range:	±10mV/m max.	Weight in water:	5Kg
System Noise Level:	5nV/m/(square root) Hz at 5Hz		
Cable drive Capability:	Over 5Km (analogue)		

4.3.3 Ultra Electronics PMES

- Ultra Electronics Electric Field Sensors are used to measure electric fields in seawater with high precision. The technology utilises specially designed Silver / Silver chloride sensor elements and extremely low noise pre-amplifiers to achieve detection in the nV/m range. The very high performance is achieved due to the exceptionally low noise of the electrodes and pre-amplifiers.
- Ultra are able to offer individual pairs of silver/silver chloride sensing elements together with matching amplifiers and filters. Such components are suitable for OEM integration.
- The Compact sensor provides a high-sensitivity device that is small, light, and easy to deploy. It is designed to be attached to a base unit, which gives stability on the seabed. The sensor has a spherical top, which contains three pairs of very low-noise electrodes. The electrodes are arranged to measure the electric field in three mutually orthogonal axes. The separation between the electrodes of each pair is 250 mm. The sensor is ready to make measurements within a very short time after deployment. There is no long stabilisation period for the electrodes, as they are already in their own electrolyte. The sphere is mounted on the top of a cylindrical pressure housing, which contains the signal

conditioning electronics. The output signals from the sensor are available via a non-metallic subsea cable connector at the base of the pressure housing. Both power supplies and signals are coupled to the sensor via this same connector. The electrode design has proved itself extremely reliable and stable in service making the Compact ideal for long-term deployment.

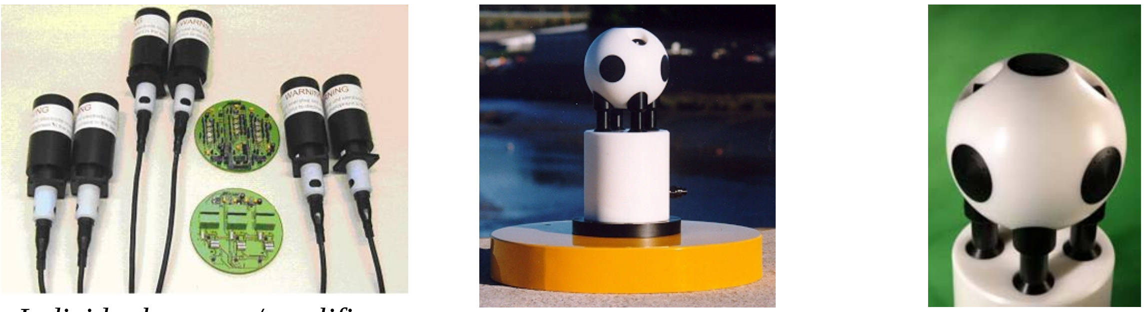

Individual sensors/amplifiers
Compact 3-axial sensor
Low-noise 3-axial sensor

Figure 4.4 Ultra Electronics PMES electric field sensors.

Individual sensor:

Sensor type	Ag/AgCl
Overall length excluding penetrator (cover fitted)	165mm
Diameter with cover fitted	70mm
Maximum working depth	4000m
Total Mass with cover fitted	700g

Complete system for OEM integration:

Measurement channels	3
Power Supply	Vs = +/-8V +/-1V DC
Power Consumption	< 5W
Power up time	< 10 minutes
Dynamic input range (within pass band)	+/-2.5mV
Bandwidth	DC to 3kHz (-3dB)
Roll off rate	6dB/octave (20dB/decade)
In band ripple	< +/-3dB
Output voltage swing	+/-5V min
Scale factor tolerance	+/-1.0%
Output type	Analogue Voltage
Equivalent input Noise at 1Hz	< 0.52 nV Hz -1/2

Compact sensor (as for OEM system above unless otherwise noted):

Measurement Axis	3 orthogonal axes
Effective sensor baseline	375mm
Power supply voltage	+/- 15V +/-0.2V DC
Power up time	10 minutes
Dynamic range	+/-1.5mV/m
Output Voltage swing	+/-10V min

Scale factor	150 microvolt/m/V
Output type	Differential voltage drive
Noise at 1Hz	<2.5nV/m / √ Hz
Noise at 0.1Hz	<6.0nV/m / √ Hz
Noise at 0.01Hz	<25nV/m / √ Hz
Dimensions - sensor assembly	Height 615mm - diameter 250mm
Weight in air	34kg
Weight in water	4kg
Depth rating	250m

Very low noise sensor:

Sensor self Noise level (1Hz to 3kHz)	1nV / m / √ Hz
Frequency range	1mHz to 3kHz
Power Supply Voltage	± 15V
Dimensions - sensor assembly	Height 1000mm, diameter 500mm
Weight in air	40kg
Weight in water	4kg negatively buoyant

4.4 Recommendation

The optimal choice of electrode material for an underwater electric field sensor would probably be carbon fibre.

One of the problems with traditional electrode materials, e.g. Ag/AgCl or zinc plates, is the slow electrochemical process before a steady equilibrium potential is obtained. That process may take up to one week for zinc electrodes. (13) Also, zinc and Ag/AgCl electrodes will wither away in seawater. However, for an expendable sea mine this might be of lesser importance.

Carbon fibre electrodes also have some advantages over bulk graphite plates. The carbon fibres are very homogeneous, have a large surface to weight ratio and are chemically inert in water.

5 FLOW SENSORS

5.1 Introduction

Ships in motion generate transverse and diverging wave components. The interference between these two waves creates a cusp locus or wake. The height of the wake generated is dependent on the vessel’s speed, shape and the depth of water through which it is moving. The wake height decays as it propagates away from the ship, so the wave height experienced at a given point is also dependent on its distance from the sailing line.

As a ship moves, water must be pushed out of its way at the bow, and drawn in behind it at the stern. There is also a flow down each side moving water from front to rear. Associated with this flow of water around the ship, there is a pressure field, which gives high pressure at the bow and stern and low pressure at the sides. The pressure affects the water surface level so that it is elevated where pressure is high; at the bow and stern, and depressed where pressure is low; at the sides. This pattern spreads to some extent into the area of water around the ship, and the depression of the water surface to the ship's sides is referred to as 'draw-down'. This is a different effect from bow and stern/wake waves, which are superimposed on this change in surface level. The changes in surface level can generally be observed along the hull of a moving ship. The water surface near the bow and stern is usually above the ship's waterline while the waterline is exposed above the water surface at mid-ships.

The ship-induced water currents are superimposed on the natural perturbations of tides, swells and waves on the seabed.

5.2 Physical principle

Traditionally, straightforward mechanical rotor- or impeller-based current meters have been widely used. They are, however, vulnerable to damage and are easily stalled by marine fouling or flotsam of various kinds. Today, acoustic measurement techniques offer the potential to overcome these limitations.

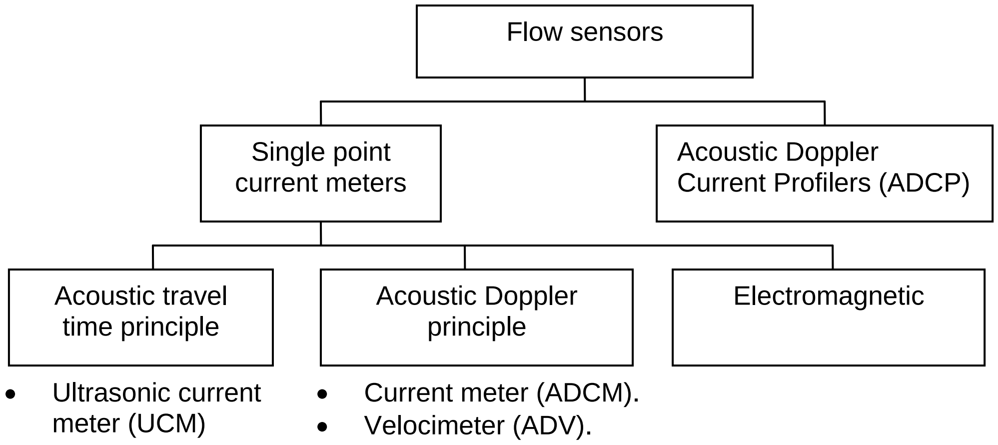


Figure 5.1 Overview of water flow (current) sensors.

Ultrasonic current meter (UCM):

These sensors measure current at a single location. Various types can be used, depending on accuracy, depth and desired measurement time. The Ultrasonic Current Meter (UCM) generates high frequency pulses in one end of the instrument, and travel time to the other side is recorded. Another sound source sends a corresponding signal in the opposite direction. The difference in travel time between the two pulses depends on the local flow velocity. Current velocity can thus be computed based on acoustic travel time difference. UCMs are usually used for small-scale measurements, such as turbulence.

Acoustic Doppler Current Meter (ADCM):
The Doppler current meter is somewhat similar to the ADCP, but measure current at a single location only. It utilizes the Doppler shift occurring when transmitting and receiving sound along two or more narrow acoustic beams. The Doppler shift is proportional to the velocity component along the beam. The data can be combined, using the exact geometry, to generate 2D (minimum 2 beams) or 3D velocity (minimum 3 beams).

Acoustic Doppler velocimeter (ADV):
The ADV uses the Doppler principle to measure the velocity of water in three dimensions. The device sends out a beam of acoustic waves at a fixed frequency from a transmitter probe. These waves bounce off on moving particulate matter in the water and three receiving probes "listen" for the change in frequency of the returned waves. The ADV then calculates the velocity of the water in the x, y, and z directions (3D).

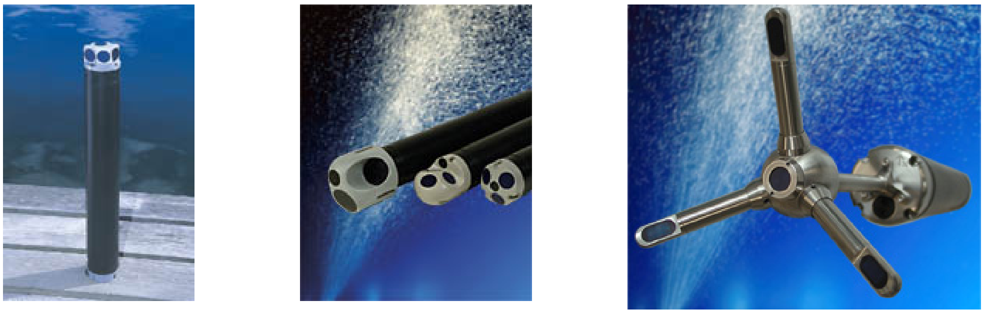
Acoustic Doppler current profiler (ADCP):
The Acoustic Doppler Current Profiler employs the Doppler principle to measure speed and direction of horizontal current velocities in a vertical profile. The instrument carries its own sound sources (sonar). By transmitting a succession of acoustic pulses, and segmenting the resulting backscatter echoes into many depth cells (bins) over a depth range of 8 to 1000 meters, computer analysis of the bins provides a detailed profile of current speed and direction throughout the water column. By combining three (or more) such sonars, any motion relative to the seabed (2D or 3D) can be calculated according to the acoustic Doppler principle.

Electromagnetic current meter:
The electromagnetic current meter measures the voltage resulting from the motion of a conductor (water flow velocity) through a magnetic field according to Faraday's law of electromagnetic induction. Simply stated, Faraday's law defines the voltage produced in a conductor as the product of the speed of the conductor (water flow velocity) times the magnitude of the magnetic field times the length of the conductor.

5.3 Sensor examples

5.3.1 Nortek AS

- All plastic and titanium parts stop corrosion.
- Small and lightweight.
- No moving parts that can be blocked or sensitive parts that are easily damaged.
- Low power consumption for long deployments.
- A variety of sensor heads and the ability to move the sampling volume away from the mounting structure assure undisturbed measurements in all situations (Aquadopp).



Aquadopp 3D current meter (ADCM)

Aquadopp Profiler (ADCP)

Vector 3D current meter (ADV)

Figure 5.2 Water flow sensors from NorTek AS.

Aquadopp 3D current meter (ADCM):
Velocity range: ±5 m/s (inquire for higher ranges).
Accuracy: 1% of measured value ±0.5 cm/s.
Maximum sampling rate (output): 1 Hz, 2 or 4 Hz on request.
Internal sampling rate: 23 Hz.
Measurement cell:
- Measurement cell size: 0.75 m.
- Measurement cell position (user selectable): 0.35–5.0 m.
- Default cell position (along beam): 0.35–1.8 m.

Doppler uncertainty (noise):
- Typical uncertainty for default configurations: 0.5–1.0 cm/s.
- Uncertainty in U,V at 1Hz sampling rate: 1.5 cm/s.

Echo Intensity:
- Acoustic frequency: 2 MHz.
- Resolution: 0.45 dB.
- Dynamic range: 90 dB.

Data Communication: RS232, RS422 or analogue outputs.
Power:
- DC input: 9–16VDC.
- Peak current: 2A at 12 VDC (user adjustable).
- Max consumption: 1Hz 0.2–1.0 W.
- Avg. consumption: 0.1 W (0.02 Hz), 0.01 W (0.002 Hz).
- Sleep consumption: 0.0013 W.

Aquadopp Profiler (ADCP):
Four acoustic frequencies: 0.4 MHz 0.6 MHz, 1 MHz and 2 MHz.
Profiling range: 60-90m (0.4 MHz), 30–50m (0.6 MHz), 12–25m (1 MHz), 5–12 m (2 MHz).
Minimum cell size: 2m (0.4 MHz), 1 m (0.6 MHz), 0.3 m (1 MHz), 0.1 m (2 MHz).
Minimum blanking 1.0m (0.4 MHz), 0.5m (0.6 MHz), 0.2m (1 MHz), 0.05 m (2 MHz).
Velocity:
- Horizontal velocity range: ±10 m/s (extended range available).
- Accuracy: 1% of measured value ±0.5 cm/s.
- Sampling rate: one second to several hours.

Data communication: RS232 or RS422.

Weight in air: 2.4 kg (2.6 kg for 0.6 MHz) with alkaline batteries.
Weight in water: Neutral.
Dimensions: 75 mm diameter, 550-600 mm length.
Materials: Standard model in plastic, full ocean depth models (2000 m and 6000 m) in titanium and plastic.
Power:

- DC Input 9–16VDC.
- Max average consumption at 1Hz: 0.2–1.5W
- Sleep consumption: 0.0013W
- Transmit power 0.3–20W, 4 adjustable levels

Vector 3D current meter (ADV):
Sampling rate: 1–64Hz output rate, internal ping rate: 100–250Hz.
Sampling volume: Height: 0.5–2cm, diameter 1.5cm.
Distance to sampling volume: 0.15m.
Velocity accuracy: 0.5% of measured value ± 0.1cm/s.
Acoustic frequency: 6.0MHz.
Data Communication: RS232 and RS422.
Weight in air (fixed stem): 5 kg, in water (fixed stem): 1.5 kg
Electronics housing: 75 mm in diameter, about 500 mm long.
Materials: Plastic (Delrin) housing and titanium probe.
Standard depth rating is 300m.
Power:

- DC Input: 9–16 VDC.
- Peak current: 2.5 A at 12 VDC (user selectable).
- Max consumption: 64Hz: 1.5 W.
- Typical consumption: 4Hz: 0.6–1.0 W.
- Sleep consumption: 0.0013 W

5.3.2 SonTek/YSI, Inc.

Argonaut-MD acoustic Doppler current meter (ADCM):
Capable of measuring water motion at a "single point" almost anywhere in the oceans, this 3D, vector-averaging current meter is small, light, and inexpensive. The MD's low-power electronics and high-capacity alkaline battery pack are perfect for long-term mooring deployments. Its high-sensitivity transducers improve performance in environments that have exceptionally low scattering conditions. With standard temperature and optional pressure and conductivity sensors, the MD is a full-featured system. It is ideal for filling holes in profiles that ADPs and ADCPs miss.

Argonaut-XR acoustic Doppler current profiler (ADCP):
The Argonaut-XR offers exceptional value for near shore deployments in less than 40 m of water. Designed specifically for mounting on the bottom of a river, channel, or harbour, the XR features a special mode that automatically adjusts one of its measurement cells for

changing water level. Its small size, rugged build, and flexible system architecture make the XR attractive for both real-time operation and autonomous deployments.

5-MHz ADVOcean acoustic Doppler velocimeter (ADV):
The ADVOcean (Acoustic Doppler Velocimeter Ocean Probe) is a versatile, high-precision instrument used to measure 3-axis (3D) water velocity in the most challenging application. The ADVOcean is designed for a wide range of environments, including the surf zone, open ocean, rivers, lakes, and estuaries. Extremely simple to set up and use, most users are collecting high-quality data within minutes of receiving the system.


Argonaut-MD *Argonaut-XR* *5-MHz ADVOcean*

Figure 5.3 A selection of current sensors from SonTek.

Argonaut-MD acoustic Doppler current meter (ADCM):
Velocity:
    Range: ±6 m/s.
    Resolution: 0.1 cm/s.
    Accuracy: ±0.1 % of measured velocity, ±0.5 cm/s.
    User programmable data output rate from 10 seconds to 12 hours.
Operating temperature: -5° to 40°C.
Storage temperature: -10° to 50°C.
Weight in air: 5.6 kg/12.5 lb (Delrin housing), 11.8 kg / 26 lbs (Titanium housing).
Weight in water: 1.4 kg/3.0 lb (Delrin housing), 7.7 kg / 17 lbs (Titanium housing).
Input power: 6-16 VDC.
Typical power consumption: 0.2 – 0.3 W (continuous operation); 0.0001 W (stand-by).
Battery capacity (alkaline): 368 w-hr.

Argonaut-XR acoustic Doppler current profiler (ADCP):
Velocity:
    Range: ±6m/s (0.003 ft/s).
    Resolution: 0.1 cm/s.
    Accuracy: (0.016 ft/s) ±1% of measured velocity, ±0.5 cm/s.
Depth rating: 200m.
Dimensions: 15.2 cm (6.0 in.) diameter by 18.0 cm (7.1 in.) height.
Weight in air: 2.5 kg (5.5 lb.).
Weight in water: -0.3 kg (-0.7 lb.).
Operating Temperature: -5° to 40°C.
Storage Temperature: -10° to 50°C.

Power:

Input power: 7-15 V DC.
Typical power consumption: 0.2 to 0.3 W (continuous operation); 0.01W (stand-by).
Battery capacity (alkaline): 400 W-hr.

5-MHz ADVOcean acoustic Doppler velocimeter (ADV):

Physical Parameters:

Weight in air: 3.18 kg/7 lbs.
Weight in water: 0.45 kg/1 lb.
Pressure rating: 60m.
3-D probe circumference: 130 mm (5.1”).
2-D probe circumference: 147 mm (5.8”).

Standard Features:

- Fixed sampling volume of 0.25cc located 10 cm from transducer.
- 3-D down-looking ADV probe on 15 cm stem.
- RS232 communication protocol.
- Flexible sampling strategies for reduced duty cycle operation and extended deployments.
- 2 Mb internal memory (over 100,000 samples).
- Acoustic altimeter.
- Temperature sensor for automatic sound speed compensation.

Velocity:

Range: ±0.001 - 4.5 m/s (±0.003 to 15 ft/s).
Resolution: 0.0001 m/s.
Accuracy: ±1% of measured velocity, ±0.001 m/s.
User programmable data output rate.

Environmental:

Operating temperature: -5° to 40°C.
Storage temperature: -10° to 50°C.

Power Requirements:

Input power: 7-30 VDC.
Typical power consumption (continuous operation): 0.2 to 0.5 W.

5.3.3 Teledyne RD Instruments.

Doppler Volume Sampler (ADCM):

The DVS offers the potential for a substantially improved quality of measurement because it can act as a high-resolution profiler. Velocity shear between bins indicates how well the measurement really represents the deployment depth. In addition, low backscatter will typically only reduce the range of the profile by eliminating bins—leaving the precision of the measurement in the remaining bins unaffected.

- Four-beam Janus configuration for a profile of the error velocity—high error velocities in the near bins would indicate inhomogeneous flow due to the mooring line.
- High precision: the DVS measures velocity profiles at up to 40 times per second, allowing mm/s precision at a 1 Hz update rate.

Workhorse Monitor (ADCP):

The Monitor offers a choice of three frequencies and ranges, to meet a wide array of data requirements. The unit also offers a flexible upgrade path, which includes an external battery pack, pressure sensor, bottom-tracking capability for moving boat applications, and directional wave measurement.

- Extreme accuracy and reliability: The Monitor is ideally suited for the most demanding environments, including high traffic areas such as ports and harbours.
- Versatility: This direct reading unit can easily be upgraded to tackle a wide variety of coastal applications. Typical upgrades include pressure sensor, external battery pack, bottom tracking, and directional wave measurement.
- Precision data: Teledyne RDI's patented BroadBand signal processing delivers very low-noise data, resulting in unparalleled data resolution and minimal power consumption.
- A four-beam solution: Teledyne RDI's patented 4-beam design improves data reliability by providing a redundant data source in the case of a blocked or damaged beam; improves data quality by delivering an independent measure known as error velocity; and improves data accuracy by reducing variance in your data.

Doppler Volume Sampler (ADCM).

Doppler Volume Sampler (ADCM).

Workhorse Monitor (ADCP).

Figure 5.4 Flow sensors from Teledyne RDI.

Doppler Volume Sampler (ADCM):

Velocity Profiling:
  Max range: 5m.
  Min blanking zone: 2cm.
  Number of bins: 1-5.
Profile Parameters:
  Velocity accuracy: 1.0% to 0.5cm/s.
  Velocity resolution: 0.1cm/s.
  Velocity range: ±6m/s.
  Sample time: 1s.
Transducer and Hardware:
  Frequency: 2400 kHz.
  Beam angle: 45°.
  Configuration: 4-beam, convex.
  Internal memory: 16MB.

Communications: RS232, inductive.
Depth ratings: 750m, 6000m.

Workhorse Monitor (ADCP):

Long Range Mode:

	Range Depth Cell (m)	Std. Dev. (m)	Size (cm/s)
1200kHz	24	2	3.8
600kHz	70	4	4.2
300kHz	165	8	4.2

Velocity accuracy:

- 1200, 600: 0.3% of the water velocity relative to the ADCP ±0.3cm/s.
- 300: 0.5% of the water velocity relative to the ADCP ±0.5cm/s.

Velocity resolution: 0.1cm/s.
Velocity range: ±5m/s (default) ±20m/s (maximum).
Number of depth cells: 1–128.
Ping rate: 2Hz (typical).
Echo Intensity Profile:
Vertical resolution: Depth cell size.
Dynamic range: 80dB.
Precision: ±1.5dB.
Transducer and Hardware:
Beam angle: 20°.
Configuration: 4-beam, convex.
Power:
Input power: 20–50VDC.
Environmental:
Standard depth rating: 200m; optional to 6000m.
Operating temperature: -5° to 45°C.
Storage temperature without batteries: -30° to 60°C.
Weight in air: 7.6kg.
Weight in water: 3.0kg.

5.3.4 Nobska

The MAVS Current Meter (UCM) is a true 3 axis Acoustic Current Meter which employs a differential travel time measurement technique. The current meter takes measurements across four acoustic axes to provide a true vector averaged velocity measurement. Programmable burst mode and triggered sampling provide the most flexible current meter available. The combination of small sensor geometry and differential travel time technique provide unsurpassed resolution and accuracy. The small transducer size significantly reduces the disturbance to water flow. While the standard range of measurement is 200 cm/sec, low speed measurement accuracy in the 0.03 cm/sec to 10 cm/sec range is preserved.

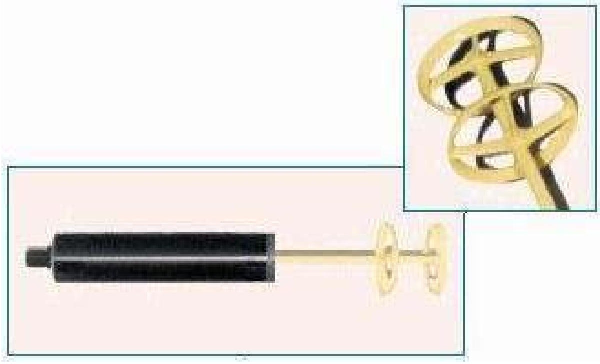


Figure 5.5 Flow sensor (UCM) from Nobska.

Parameter	Accuracy	Resolution	Range
Speed	0.3 cm/sec	0.03 cm/sec	200 cm/sec (optional ranges available)
Direction	± 2 °	1°	360 °
Temperature	0.1 °C	0.03 °C	-5 to 45 °C
Conductivity	0.2 mS/cm	0.02 mS/cm	0 - 75 mS/cm
Pressure	0.5 % F.S 0.04 % optional 0.08 % optional	0.024 % F.S.	15, 30, 60, 450, 3,000, 7,500 & 10,000 PSI
Tilt	2 °	0.1 °	20 °, 45 ° optional

Drift: 0.15 cm/sec per month.

Measurement Technique: Differential travel time, 3 axis.

Acoustic Paths: 4 measured, 4 used.

Power:

External power: 12-15 VDC.

Current Drain: 23 mA (measuring), 0.6 mA (sleep mode).

Communications: TTL, RS-232 or RS-485 @ 38,400 baud maximum 115.2 K baud.

Depth: 2000 m. or 6000 m.

Dimensions:

Cylinder Diameter: 3.25 in.

Overall Length: 25 in.

Weight:

Water: 2.6 lbs, air: 5 lbs.

Sampling Rates:

- 10 Hz in earth coordinates (resolved to Ve, Vn, Vup).
- 15 Hz in instrument coordinates.
- 25 Hz raw data, no compass, no options.

5.3.5 InterOcean Systems Inc.

The S4 electromagnetic current meter is designed to measure the true magnitude and direction of horizontal current motion in any water environment. The voltage is sensed by the two pairs of titanium electrodes located symmetrically on the equator of the sensor. The data obtained is then stored in non-volatile solid-state memory.

The S4 measures the voltage resulting from the motion of a conductor (water flow velocity) through a magnetic field. The magnetic field intensity is generated by a circular coil, internal to the S4, driven by a precisely regulated alternating current. The use of an alternating magnetic field and synchronous detection techniques to measure the voltage at the sensing electrodes provides an extremely stable, low noise current measurement. Two orthogonal pairs of electrodes and an internal flux gate compass provide the current vector.

The instrument itself is the self-contained current measuring sensor, enclosing all necessary solid-state electronics for acquiring, processing and outputting data.

Figure 5.6 Electromagnetic current meters from InterOcean Systems Inc.

Current Speed:
Range: 0-350 cm/sec (standard), 0-50, 0-100, 0-600, 0-750 cm/sec.
Accuracy: 2% of reading +/- 1 cm/sec.
Sampling Rate: S4/S4A: 2 Hz, S4AH: 5 Hz.
Resolution: 2 Hz: 0.03 to 0.35 cm/sec, 5 Hz 0.037 to 0.43 cm/sec (depending on range).
Noise: Less than the resolution for averages of 1 minute or longer.
0.05 cm/sec rms for 10 second averages.
0.25 cm/sec rms for 2 second averages.
0.75 cm/sec rms for burst sampling (0.5 second rate).
Threshold: Equal to resolution.
Vertical Response: True cosine response (internally software corrected with tilt option).

Direction:
Type: Flux-gate compass.
Range: 0-360.
Resolution: 0.5 deg.
Accuracy: +/- 2 deg within tilt angles of 5 deg.
Tilt: +/- 4 deg for tilt angles between 15 and 25 deg.
Power Supply:
Type: Internal batteries (6 Alkaline "D" cells), (Lithium optional).
Endurance:
Alkaline cells: 440 hours continuous logging.
Lithium option: 1,600 hours continuous logging.

Mechanical:

Size: S4: 25 cm (10 in) diameter.
S4 Deep: 35.5 cm (14 in) diameter.
Weight: S4 air: 11 kg (24 lb.), water: 1.5 kg (4 lb.).
S4 Deep air: 34.5 kg (76 lb.), water: 10.5 kg (23 lb.).
Material: Sphere, glass-filled cycloaliphatic epoxy.
Mooring rod, Titanium 6 AL-4V.
Drag: S4: 4 kg (9 lb.) at 250 cm/sec (8 ft/sec).
S4 Deep: 0.63 kg (1.4 lb.) at 50 cm/sec, 15.68 kg (34.57 lb.) at 250 cm/sec.
Depth: S4: 1,000 m (3,200 ft) maximum.
S4 Deep: 6,000 m (19,200 ft) maximum.
Temperature:
Storage: -40 to +50 deg C.
Operating: -5 to +45 deg C.

5.4 Recommendation

Velocimeters, with their protruding probes, may represent a mechanical challenge with respect to mine handling and deployment on the seabed. These sensors also are more likely to be damaged by fishing operations such as trawling. Electromagnetic and Doppler current sensors do not have these limitations, and are thus a better choice for sea mines.

Travel time measuring current sensors must have its sound transmitter in close proximity to the receiver. Therefore, the effectiveness of the acoustic travel time meter is limited by its power consumption. Doppler current meters can sense currents at a further distance from the transducer. As a result, the required power is decreased. Like the Doppler velocimeters, travel time sensors have protruding probes that are prone to be damaged by fishing equipment. For these sensors, it is also very important for the probes to be mechanically aligned so that the travel time will get properly measured.

The Doppler profilers have the ability to measure flow in different layers of the water column, and some shallow water current profilers can both measure the currents and the wave height/direction. These sensors will probably offer a great potential for future sea mines even though they may be detected by their active utilization of acoustics.

6 SEISMIC SENSORS

6.1 Introduction

As a ship moves through the water, acoustic noise is generated from propellers, engines, and other machinery. The hull and structural arrangement can also contribute to the overall picture by generating flow noise and flow induced resonances.

The hydrodynamic noise from the ship propagates through the water and reaches the seabed. Here, a part of it is coupled into seismic motion of the solid matrix of the soil. Seismic sensors are designed to detect small structural vibrations, and can thus pick up the ship's signature through movements of the sensor case.

6.2 Physical principle

Instrumental seismology all started with being able to measure the ground motion. Thus, seismologists usually talk about ground displacement (formally measured in meters). On the other hand, engineers seem to think that acceleration (m/s^2) is the most natural unit, since it is directly related to force and the peak ground acceleration is an often-quoted measure.

Earlier, analogue instruments were usually made to record one type of ground motion like velocity. Traditionally, seismologists prefer recording weak motion displacement or velocity, for easy interpretation of seismic phases, while engineers use strong motion acceleration, whose peak values are directly related to a structure's seismic load. Today it makes less of a difference, since due to advancement in sensor and recording systems, the weak motion instruments can measure rather strong motions and the strong motion sensors are almost as sensitive as the weak motion sensors. The digital recording furthermore makes it easy to convert from acceleration to velocity etc. (4) An overview of different sensor technologies is depicted in Figure 6.1.

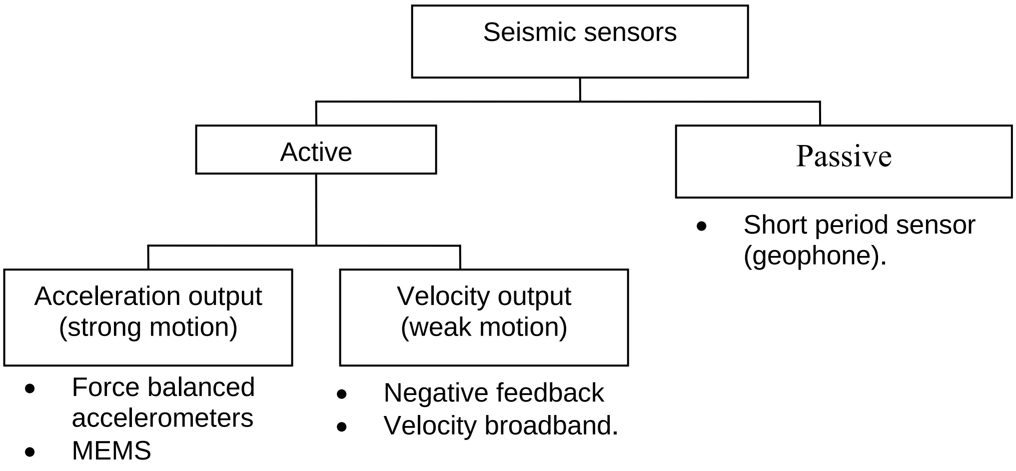


Figure 6.1 Overview of seismic sensor technologies.

Short period sensor (geophone):
Nearly all traditional seismometers use a velocity transducer to measure the motion of the mass. The principle is to have a moving coil within a magnetic field. This can be implemented by having a fixed coil and a magnet that moves with the mass or a fixed magnet and the coil moves with the mass. The output from the coil is proportional to the velocity of the mass relative to the frame (see Figure 6.2). (4)

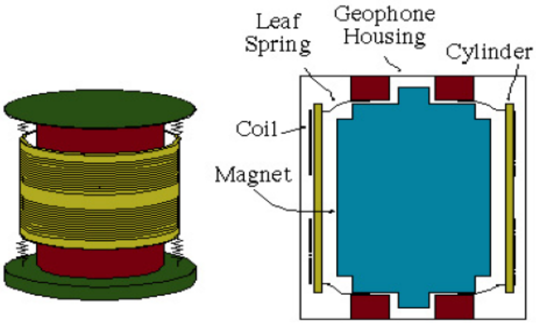


Figure 6.2Physical principle of a geophone.

Force balanced accelerometers (FBA):
The new key element in this sensor is the displacement transducer. A velocity transducer (as for the geophone) cannot be used since it has too low sensitivity at low frequencies. The displacement transducer normally uses a capacitor C, whose capacitance varies with the displacement of the mass. A current, proportional to the displacement transducer output, will force the mass to remain stationary relative to the frame. The MEMS (micro electro-mechanical systems) accelerometer is an example of an FBA. (4)

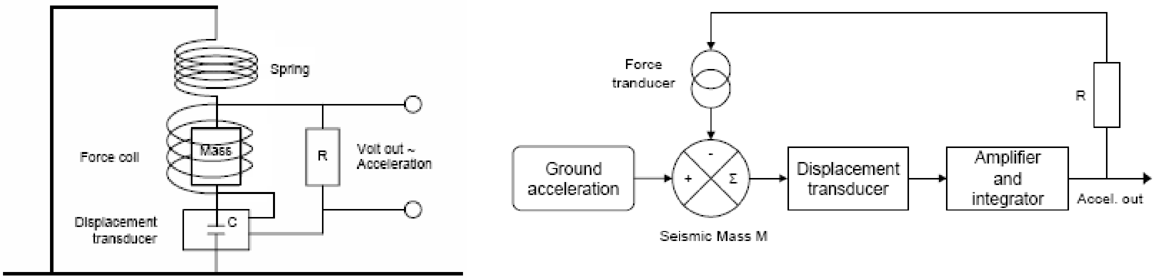


Figure 6.3 Physical principle for the FBA.

Velocity broad band (VBB):
Broadband in seismology means from long periods (about 0.01 Hz) to frequencies of some tens of Hz. Since the sensitivity to velocity increases proportional to frequency, a very sensitive accelerometer is easily saturated by noise at high frequency. At low frequencies, a permanent offset is easily generated (tilt or temperature) and might be saturating the system. Output signals at low frequency would be very low compared to levels at high frequency, requiring a very large dynamic range of the recording system. By changing the accelerometer to have a band-limited output proportional to velocity, the above-mentioned problems can essentially be voided. (4)

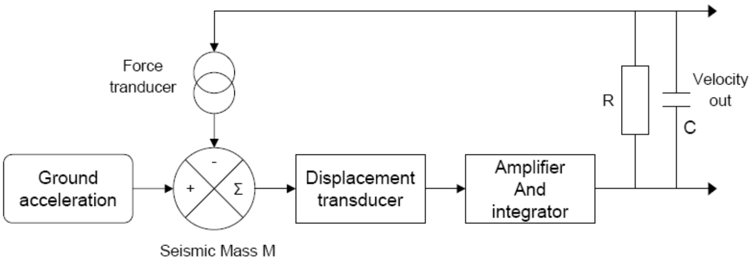


Figure 6.4 Physical principle for a VBB type sensor.

Negative feedback:
The simplest way of extending the frequency response of the VBB sensor, is to use feedback. The FBA sensors are specially made for feedback with a feedback coil and a displacement transducer. However, it is also possible to use feedback with a standard velocity transducer using the signal coil for both signal pickup and feedback. The advantage of this design is that quality sensors with extended frequency response can be constructed with inexpensive sensors like geophones. (4)

6.3 Sensor examples

6.3.1 Miscellaneous companies

Seismologists have become increasingly interested in using low cost accelerometers for earthquake monitoring and strong motion detection in particular. A new breed of accelerometers is becoming available at a price point and performance level that enables the deployment of high-density arrays. The use of Micro Electro Mechanical Systems (MEMS) devices offers many benefits over conventional sensors, which makes them attractive in specific applications where economics or budget limitations are important. However, geophones' resolution or dynamic range is still typically three orders of magnitude better than that offered by existing micro-machined accelerometers.

Broadband seismology, or the analysis of mostly weak ground motion with a period ranging from 1 second up to 300 seconds, requires instruments capable of generating high dynamic range (154 dB +) velocity responses. The best broadband seismometers have a noise floor below the background Earth seismic noise. Prices for such instruments range from a few hundreds of dollars at the low end, to tens of thousands of dollars for the most sophisticated and least noisy equipment. They typically use 16- or 24-bit digitizer modules and data acquisition systems. (6)

Below are some information about common commercial seismometers and accelerometers (see Table 6.2, Table 6.3, Table 6.4 and Table 6.4). Abbreviations are: C: Number of components, f-range: Frequency range in which the response is flat (Hz), Out V: max voltage out (0-pV), In V: Supply voltage (V), W: Power used (W), G: Generator constant (sensivity) (V/ms-1 or V/g), Wt: Weight of sensor (kg), Dyn. range: Dynamic range (dB), Res: Resolution in nm/s or µg, f0: Natural frequency (Hz), Dam: Open circuit damping, Rg: Generator coil resistance(ohm), CDR: Critical damping resistance (ohm), Rc: Calibration coil resistance (ohm), K: Calibration coil motor constant, Dyn: Dynamic range (dB) and Mov: Free motion of the mass (mm).

SHORT PERIOD	**C**	**f0**	**Dam**	**Wt**	**Rg**	**CDR**	**Rc**	**G**	**K**	**Dyn**	**Mov**
Geodevice JC-V103	1	1.0	0.01		1000					100	5.0
Geodevice JC-V104	3	1.0	0.7		350		70				
Geodevice JC-45-3	3	4.5	0.02		300		yes				2.0
Geo Space GS1	1	1.0	0.54	0.70	4550			280			
Geo Space GS-11D	1	4.5	0.34	0.023	380			32			1.8

Geo Space HS-1	1	4.5	0.28	0.028	1295			45			
Geotech S-13	1	1.0	~0.02	5.0	3600	6300	23	629	0.198	164	3.0
Geotech S-13J	1	1.0		0.9	6400		20	344		140	1.5
Input/Output SM-6	1	4.5	0.26	0.016	375		---	28	---		4.0
Kinemetrics Ranger SS1	1	1.0	0.07	1.45	5000	6530	100	345	0.40		
Mark products L4C	1	1.0	0.28	1.0	5500	8905	yes	276			6.2
Mark products L4A	1	2.0	0.28	0.5	5500	8905		276			
Mark products L22	1	2.0						88			
Mark products L28B	1	4.5	0.48	0.02	395			35			2.0
Sprengnether S6000	3	2.0		0.5	280			45	0.44		

Table 6.1 Commercial short period geophones (from (5)).

Kinemetrics SS-1 *Geodevice JC-V104* *GeoSpace GS-1* *GeoTech S-13J*

Figure 6.5 Short period seismometers (geophones).

NEGATIVE FEED BACK	C	f-range	Out V	In V	W	G	Wt	Dyn	Res
GeoDevice FSS-3B	3	1-40	8	12	0.6	800	12	120	
GeoSIG VE53	3	1-50	10	12	0.5	1000	2.5	120	
Geotech KS-10	1	0.05-20				500	3	140	
Kinemetrics WR –1	1	0.05-20	2.5	±12	0.3	160	4	125	
Lennartz LE-3Dlite	3	1-80	5	12	0.1	400	2	120	3nm/s, 1Hz
Lennartz LE-3D/5s	3	0.2-40		12	0.1	400	7	120	1nm/s, 1Hz
Lennartz LE-3D/20s	3	0.05-40	10	12	0.6	1000	7	120	2nm/s, 1Hz

Table 6.2 Commercial negative feedback seismometers (from (5)).

Lennartz LE-3Dlite

GeoSig VE-53

Geodevice FSS-3B

Figure 6.6 Negative feedback seismometers.

ACCELEROMETERS	C	f-range	Out V	In V	W	G	Wt	Dyn	Res
Akashi V450	1	DC-6	6.6	±12		50.2	8.6		0.005 µg
Eeantec EA-140	3	DC-100	5	12	0.4	5.0		140	2 µg
GeoDevice BBAS-2	3	DC-	5	12	0.4	2.5	2	135	
GeoSIG AC63	3	DC-100	10	12	0.8	5.0	3	120	
GeoSIG AC23	3	0.1-50	10	±12	0.5	10.0	2.5	102	
Geotech PA-22	3	DC-50	4.5	±15	0.5	2.25	5	114	10 µg
Geotech PA-23	3	DC-100	10	12	1.1	2.5	4.8	148	
Güralp CMG-5	3	DC-100	5	12	1.2	5.0	5	155	
Input/Output SF3000	3	DC-100	3.6	±12	0.4	1.2	0.5	120	0.3 µg
Kinemetrics FBA-23	3	DC-50	2.5	±12	0.2	2.5	2	135	
Kinemetrics EpiSensor	3	DC-200	10	12	0.4	2.5		155	
Sprengnether FBX23	3	DC-50	10	±12	0.4	10	1	90	11 µg
Sprengnether FBX26	3	DC-50	10	±12	0.2	10	1	135	0.4 µg

Table 6.3 Commercial accelerometers (from (5)).

Kinemetrics EpiSensor ES-T

GeoTech PA-23

GeoSig AC-63

Figure 6.7 Force balanced accelerometers.

VELOCITY BB	C	f-range	Out V	In V	W	G	Wt	Dyn
Eentec P-123	3	0.1-50	10	12	0.2	2000	5	130
Eentec R1 rotational	3	0.05-20	5	12	0.2	50	1	106
Eentec EP-105	3	0.03-50	10	12	0.2	2000	5	135
Eentec EP-300	3	0.017-50	7.5	12	0.4	2000	9.5	150
Eentec PMD223	3	0.017-32	7.5	12	0.3	2000	11	146
Eentec PMD103	3	0.033-50	10	12	0.5	2000	5.3	132
Geodevice FBS-3	3	0.05-40	10	12	0.6	1000	12	120
Geodevice MBS-1	3	0.017-50	10	12	2.0	1000	12	140

Geodevice BBS-1	3	0.008-50	10	12	2.0	1000	14	140
Geotech KS-2000	3	0.01-50	10	12		2000	7	160
Geotech KS-54000 IRIS	3	0.003-5	20	24	1.2	2400	66	
Güralp CMG-1T	3	0.003-50	10	12	0.7	1500	14	
Güralp CMG-3T	3	0.003-100	10	12	2.9	1500	12	180
Güralp CMG3-ESP	3	0.1-50	10	12	0.9	2000	9	170
Güralp CMG-6T	3	0.03-100	10	12	0.8	1500	3	
Güralp CMG-40T	3	0.03-50	10	12	0.6	3200	7	145
Nanomtrics Trillium	3	0.033-30	8	12	0.4	1500	11	
Sprengnether S-3000Q	3	1-250		±12	0.1	278	2	
Sprengnether WB 2023	3	0.03-20	36	12	0.2	1000	5	
Sprengnether WB 2123	3	0.016-50	36	23		1000	5	
Streckeisen STS-2	3	0.033-	20	12	1.8	1500		145
Streckeisen STS-1	1	0.003-10						

Table 6.4 Commercial velocity broad band seismometers (from (5)).

Eentec EP-105

GeoTech KS-2000

Güralp CMG-3T

Figure 6.8 Velocity broadband seismometers.

6.3.2 Colibrys

The Si-Flex™ SF3000L is a closed-loop accelerometer based on Micro-Electro-Mechanical System (MEMS) technology that offers unmatched noise performance and robustness. Si-Flex™ accelerometers are a product of the world-class MEMS fabrication and design facility of Colibrys (former Applied MEMS, Inc.).

Figure 6.9 MEMS accelerometer from Colibrys.

Linear output range: ±3 g peak.
Sensivity: 1.2 V/g.
Frequency response: DC to 1000 Hz.
Dynamic range (100 Hz bandwidth): 120 dB.
Noise (10 to 1000 Hz): 300 to 500 $ng_{rms}/\sqrt{Hz}$.
Cross-axis rejection: > 46 (34 min.) dB.
Shock limit (0.5 ms ½ sine): 1000 g peak.
Vibration (20 – 2000 Hz): 60 g pk-pk.
Operating temperature range: -40 to +85 °C.
Sensivity temperature coefficient: 75 ppm/°C.
Offset thermal coefficient: ±100 µg/°C.
Linearity error: ±0.1 % full scale.
Input voltage: ±6 to ±15 Volts DC.
Quiescent current: < 30 mA.
Self test: TTL level voltage.
Weight: 1 lb.
Enclosure moisture rating: 67 IP rating.

6.4 Recommendation

An important drawback with traditional geophone-based seismometers is low mechanical shock tolerance. In this area, MEMS sensors are superior. However, MEMS seismometers have low sensitivity as compared to the geophones. It seems that geophones might still be the best choice for underwater signature assessment, in spite of their handling and deployment precautions.

7 PRESSURE SENSORS

7.1 Introduction

The pressure signature arises from the reduction in pressure associated with a fluid moving over a surface – Bernoulli’s principle. It is limited to the vicinity of the ship. In shallow waters, the sea floor pressure rises slightly as the bow passes and then drops below the original level. It rises again as the stern passes and then returns to normal. The magnitude and duration are related to the hull shape, the water depth and the ship speed. The ship-induced fluctuations are superimposed on the nominal static depth pressure at the sea floor and on the natural perturbations of tides, swells and waves. Waves and swells, typically with periods between 1 and 30 seconds, may mask the ship-induced changes of similar duration. Higher frequency, lower magnitude variations of less than 1 mm may also arise from wind wavelets and from passing ships. For accurate data interpretation, the actual depth of the water at the time of measurement is needed. Thus, for measurements in say 35 m of water, a dynamic range in excess of 90 dB is required. (2)

7.2 Physical principle

Potentiometric:
These sensors use a Bourdon tube, capsule, or bellows to drive a wiper arm on a resistive element. For reliable operation, the wiper must bear on the element with some force, which leads to repeatability and hysteresis errors. These devices are very low cost, however, and are used in low-performance applications such as dashboard oil pressure gauges. (7)

Inductive: Several configurations based on varying inductance or inductive coupling are used in pressure sensors. They all require AC excitation of the coil(s) and, if a DC output is desired, subsequent demodulation and filtering. The linear variable differential transformer (LVDT) types have a low frequency response due to the necessity of driving the moving core of the differential transformer. The LVDT uses the moving core to vary the inductive coupling between the transformer primary and secondary. (7)

Capacitive: Capacitive pressure sensors typically use a thin diaphragm as one plate of a capacitor. Applied pressure causes the diaphragm to deflect and the capacitance to change. This change may or may not be linear and is typically in the order of several picofarads out of a total capacitance of 50-100 pF. The change in capacitance may be used to control the frequency of an oscillator or to vary the coupling of an AC signal through a network. The electronics for signal conditioning should be located close to the sensing element to prevent errors due to stray capacitance. If the dielectric constant of the material between the plates is not kept constant, errors may result. Capacitive absolute pressure sensors with a vacuum between the plates are ideal in this respect. Because the capacitance of this sensor depends only on physical parameters, sensors with good performance can be constructed using materials with low coefficients of thermal expansion. Since the device has to be large to obtain a usable signal, frequency response may be a problem in some applications. In addition, low-pressure capacitive sensors exhibit acceleration and vibration sensitivity due to the necessity for a large, thin diaphragm. (7)

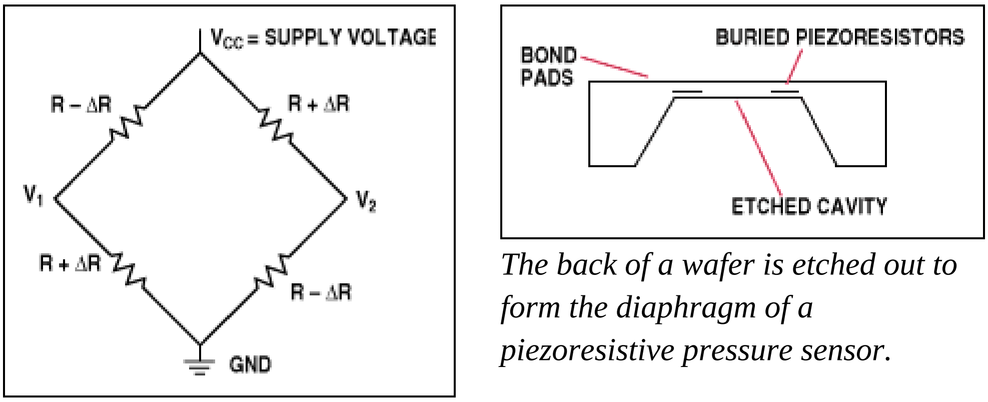
Piezoelectric: Piezoelectric elements are bi-directional transducers capable of converting stress into an electric potential and vice versa. They consist of metallised quartz or ceramic materials. One important factor to remember is that this is a dynamic effect, providing an output only when the input is changing. This means that these sensors can be used only for varying pressures. The piezoelectric element has a high-impedance output and care must be taken to avoid loading the output by the interface electronics. Some piezoelectric pressure sensors include an internal amplifier to provide an easy electrical interface. (7)

Metallic Strain Gauge: Strain gauge sensors originally used a metal diaphragm with strain gauges bonded to it. A strain gauge measures the strain in a material subjected to applied stress. Metallic strain gauges depend only on dimensional changes to produce a change in electrical resistance. Stress applied to a metallic strip causes it to become slightly longer, narrower and thinner, resulting in a change in resistance. Metallic strain gauges can also be formed on a diaphragm by means of thin film deposition. This construction minimizes the effects of repeatability and hysteresis that bonded strain gauges exhibit. These sensors exhibit the relatively low output of metallic strain gauges. (7)

Semiconductor Strain Gauge (Piezoresistive): These are widely used; both bonded and integrated into a silicon diaphragm, because the response to applied stress is an order of magnitude larger than for a metallic strain gauge. When the crystal lattice structure of silicon is deformed by applied stress, the electrical resistance changes. This is called the piezoresistive effect. A silicon bar may be bonded to a diaphragm to form a sensor with relatively high output. Making the diaphragm from a chemically inert material allows the bonded semiconductor strain gauge sensor to interface with a wide variety of media. (7)

Piezoresistive Bridge: IC processing is used to form the piezoresistors on the surface of a silicon wafer. There are four piezoresistors within the diaphragm area on the sensor. Two are subjected to tangential stress and two to radial stress when the diaphragm is deflected. Etching of the back of the wafer is used to form the diaphragm. See Figure 7.1. The high output of the bonded strain gauge is combined with the low hysteresis of the deposited strain gauge in this design, due to the integrated construction and the nearly perfect elasticity of single-crystal silicon. The cost of the sensing element is low since a large number of devices fit on a silicon wafer. Typical die size is 0.1 in. square with a 50 mil square diaphragm. The circuitry needed for amplification, temperature compensation, and calibration may be included on the same IC. Various pressure ranges are accommodated by varying the diaphragm thickness and, for very low pressures, by varying the diaphragm diameter. This device can be used to construct absolute, differential, and gauge pressure sensors, depending on the reference. Because the sensing element is so small, the package can have a great deal of mounting and port interface flexibility. In addition, the small size means that it has a wide frequency response. Thus, it may be used for dynamic pressure measurements without concern about errors. Mechanical vibration and acceleration have a negligible effect. (7)

Quartz crystal resonator:
This type of pressure sensor uses a precision quartz crystal resonator whose frequency of oscillation varies with pressure-induced stress. The resonant frequency outputs are maintained and detected with oscillator electronics similar to those used in precision clocks and counters.



The back of a wafer is etched out to form the diaphragm of a piezoresistive pressure sensor.

Figure 7.1 Piezoresistive bridge pressure sensors incorporate four piezoresistors in the diaphragm. When the diaphragm is deflected, two resistors are subjected to tangential stress and two to radial stress. The four are connected to a four-element bridge. (7)

7.3 Sensor examples

7.3.1 Paroscientific, Inc.

Digiquartz® Depth Sensors provide high precision water level measurements. Typical application accuracy of 0.01% is achieved even under difficult environmental conditions. Desirable characteristics include excellent long-term stability, 1 x 10^{-8} resolution, low power consumption, and high reliability. The remarkable performance of these depth sensors is achieved using a precision quartz crystal resonator whose frequency of oscillation varies with pressure-induced stress. A quartz crystal temperature signal is provided to thermally compensate the calculated pressure and achieve high accuracy over a broad range of temperatures. The depth sensors include waterproof housings with integral shock protection. High accuracy, resolution, and stability make Digiquartz® Depth Sensors ideal for applications such as Tsunami detection, wave and tide gauges, platform levelling, underwater pipe laying, and as depth sensors in ROVs and AUVs. All Depth Sensor ranges are available with either frequency outputs or integral intelligent electronics with bi-directional digital communications.

Figure 7.2Paroscientific Digiquartz® Depth Sensor Model 8CDP.

Digiquartz® Depth Sensor Model 8CDP:
Absolute range:
 0-10 m H_2O to 0-7000 m H_2O
 0-30 psia to 0-10,000 psia
Gauge range:
 0-10 m H_2O to 0-140 m H_2O
 0-15 psig to 0-200 psig

Resolution: 1 x 10^{-8}.
Accuracy: Typically better than 0.01%.
Calibrated Temperature: -2°C to +40°C.
Hysteresis: ≤± 0.005% Full Scale.
Repeatability: ≤± 0.005% Full Scale.
Over Pressure: 1.2 times Full Scale.
Thermal Sensitivity: <0.0008% Full Scale /°C.

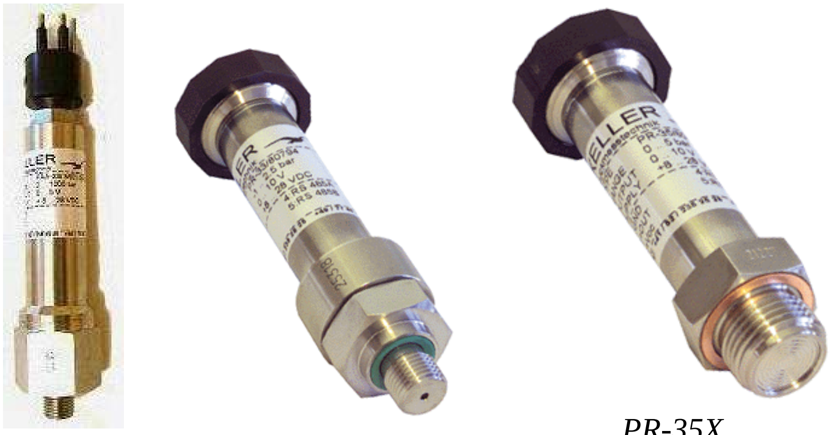
Input voltage: 6 - 16 VDC.
Current consumption: 16.5 mA quiescent, 32 mA max @ +6 VDC.

Output signal: RS-232 or RS-485 meets EIA/TIA specs.

Diameter: 8.9 cm.
Length:
    Absolute version: 21.7cm, 700m version: 26.7 cm.
    Gauge version: 22.4 cm.
Weight:
    3.48 lbs (1.58 kg) max.
    700m version: 5.0 lbs (2.26 kg) max.
Housing Materials/Wetted: PVC type 1 or acetal, white.

7.3.2 Omni Instruments

The series 33 sub sea high precision pressure sensor combines the latest technologies of both pressure sensing and electronic compensation. The pressure sensor is a high stability piezoresistive device designed for use in transmitters where accuracy and stability are essential. The sensing component is a micro-machined silicon chip of high sensitivity mounted in a floating arrangement. An independent temperature sensor is integrated on the surface of the silicon chip. The processing electronics comprise a PIC 14000 microprocessor with an integral 13…14 bit A/D converter and inputs capable of handling five signals. Conversions are performed at a rate of at least 100 operations per second. The pressure signal compensation uses a mathematical model based on polynomial approximation, which provides almost perfect compensation over the operating temperature range. The voltage (or current) analogue output signal is generated by a 16-bit D/A converter. The output signal is updated every 10 milliseconds. Via the RS485 interface, the user can set the zero and the gain of the transmitter by simple software programming. The transmitter can be produced with various types of pressure connections. Among its features are standard plates that hold the connector, enabling the same transmitter to be supplied with different electrical connectors that can be exchanged by the user as an option. The Series 33 transmitters have an exceptional price/performance ratio.



PA(A)-33 *PR-33X* *PR-35X*

Figure 7.3 Pressure sensors from Omni Instruments.

PA(A)-33:

Standard pressure ranges (bar, FS):
- PAA-33: 1, 3, 10, 30.
- PA-33: 1, 3, 10, 30, 100, 300, 1000, 1360.
- Overpressure: -1, 3, 7, 20, 60, 200, 300, 1000, 1360.

Storage-/Operating Temperature Range: -40…80 °C.
Compensated Temperature Range: 10…40 °C (optional: -10…80 °C).
Accuracy:
- (10…40 °C): 0.05 %FS.
- (-10…80 °C): 0.1 %FS.

True Output Rate: 100 Hz.
Resolution: ≤0.01 %FS.
Long Term Stability (typical):
- Range ≤2 bar: 0.5 mbar.
- Range > 2 bar: 0,05 %FS.

Output Signal: 4-20 mA (2 wire), 0-10 V (3 wire).
Supply (U): 8-28 VDC (2-wire), 13-28 VDC (3-wire).
Load Resistance (Ω): (U-5V) / 0.02A (2-wire), > 5 000 (3-wire).
Pressure Endurance: 10 Million Pressure Cycles 0-100 %FS at 25 °C.
Vibration Endurance: 20 g, 20-5 000 Hz.
Shock Endurance: 20 g sinus 11 msec.
Material in Contact with Media: Stainless Steel 316L (DIN 1.4435) / Viton.

PR-33-X and PR-35-X:

Standard pressure ranges (bar, FS):
- PR 33 X / PR 35 X: 1, 3, 10, 30.
- PAA 33 X / PAA 35 X: 0.8... 1.2, 1, 3, 10, 30, 100, 300, 1000.
- Overpressure: 2, 5, 20, 60 ,200, 400, 1000.

	(digital)	(analogue)	(analogue)
Output:	RS485	4-20 mA (2 wire)	0-10 V (3 wire)
Supply (U):	8-28 VDC	8-28 VDC	13-28 VDC
Accuracy, Error band (10…40 °C):	0.05 %FS	0.15 %FS	0.1 %FS
Accuracy, Error band (-10…80 °C):	0.1 %FS	0.2 %FS	0.15 %FS

True Output Rate: 400 Hz.
Resolution: 0.002 %FS.
Long Term Stability (typical):
- Gauge: 1 mbar or 0.05 %FS.
- Absolute: 0.5 mbar or 0,025 %FS (10…40 °C).

Load Resistance (Ω): <(U-7V) / 0.02A (2-wire), > 5 000 (3-wire).
Storage-/Operating Temperature Range: -40…120 °C.
Pressure Endurance: 10 Million Pressure Cycles 0-100 %FS at 25 °C.
Vibration Endurance: 20 g (5 - 2 000 Hz, max. amplitude ± 3 mm).
Shock Endurance: 20 g (11 msec).
Material in Contact with Media: Stainless Steel 316L (DIN 1.4435) / Viton.

7.3.3 Aanderaa Instruments

Pressure Sensor 4017:

- A compact fully integrated pressure sensor for measuring water pressure.
- Easy integration as OEM sensor in most measuring systems.
- Range up to 60MPa.
- The pressure sensor is housed in a rugged titanium cylinder.
- The sensing element is based on a silicon piezoresistive bridge sampled and temperature compensated by an advanced DSP.
- Since all calibration and temperature compensation data is stored internally, the pressure can be presented directly in engineering units without external calculation.

Figure 7.4 Pressure sensor from Aanderaa Instruments.

Pressure:
    4017A Range: 0 – 1 MPa (0 – 145 psia).
    4017B Range: 0 – 4 MPa (0 – 580 psia).
    4017C Range: 0 – 10 MPa (0 – 1450 psia).
    4017D Range: 0 – 20 MPa (0 – 2900 psia).
    4017E Range: 0 – 40 MPa (0 – 5800 psia).
    4017F Range: 0 – 60 MPa (0 –8700 psia).
    Resolution: ±0.02% FSO.
    Accuracy: ±0.04% FSO.
Temperature:
    Range: 0 – 36°C (32 – 96.8˚F).
    Resolution: 0.01°C (0.018°F).
    Accuracy: ±0.1°C (0.18°F).
    Response Time (63%): <10 seconds.
Output format: Aanderaa SR10 and ASCII RS-232.
Sampling interval: 2s – 255 minutes.
Supply voltage: 6 to 14VDC (SR10: -6 to -14VDC)
Current drain(@ 9V):
    Average:
        RS-232: 14mA/S +0.25mA where S is sampling interval in seconds.
        SR10: 3 mA/T where T is recording interval in minutes.
    Maximum: 50 mA.
    Quiescent: 0.25 mA (SR10, 0mA).
Operating temperature: -5 – +40˚C (23 – 104˚F).
Dimensions (DxH): O.D.36 x 86mm (O.D1.4”x3.4”).
Weight: 160g (5.47oz).
Materials: Titanium and epoxy coating.

7.3.4 GE Sensing (Druck Incorporated)

PTX 300 series:

- Ranges from 1000 to 15,000 psi.
- External/ambient pressure up to 4000 psi.
- Better than 0.1% accuracy.
- High reliability and excellent long-term stability.
- All welded construction, high containment.
- Customized designs available.

The PTX 300 series of pressure transmitters has been developed for the offshore oil and gas industries as a compact, high performance device for reliable and long-term subsea use. Maintenance free, it is available with operating ranges up to 15,000 psi and is submersible with an ambient pressure rating up to 4000 psi. Originally designed for aerospace hydraulic systems, the PTX 300 series utilizes micro-machined piezoresistive silicon technology, continually developed and proven by Druck for 30 years. The product is packaged to suit the specific requirements of subsea hydraulic control systems. In particular, the high-pressure containment rating, hydraulic transient protection and integrity of cable/electrical connections combine with the precision measuring technology to make the PTX 300 series a leader in this field.

Figure 7.5 Pressure sensor series PTX 300 from Druck Inc (GE Sensing).

Pressure ranges: Any full-scale range and engineering units may be specified between 0-1000 and 0-15,000 psi, sealed gauge or absolute.
Proof pressure: Tested to 1.5 x F.S.
Overpressure: The operating pressure range can be exceeded by 2 x F.S. to 23,000 psi, whichever is less.
Secondary containment pressure: The transmitter will safely contain up to 16,000 psi without leakage of pressure media.

Pressure media: Fluids compatible with a fully welded assembly of Inconel 625 Hastelloy and Stainless Steel. Other materials available - please refer to Druck.

Supply voltage: 10-32 VDC.
Supply sensitivity: ±0.005% F.S./Volt.
Insulation Resistance: >100MΩ at 500VDC.
Output Current: 4 to 20mA (2-wire) proportional for zero to full-scale pressure.

Accuracy: Combined non-linearity, hysteresis and repeatability: ±0.1% F.S. B.S.L.
Zero offset and span setting: ±1% F.S. nominal at 23 C.
Long-term stability: At standard reference conditions, any calibration change will not exceed ±0.1% F.S. per annum.

Temperature range:
    Process/ambient: -40 to 80°C.
    Compensated: -20 to 50°C.
    Storage: -40 to 80°C.
Temperature effects: ±0.5% F.S. Total Error Band.
Weight: 9.5 oz nominal.

7.4 Recommendation

There is a broad selection of pressure sensors on the marked today. In this report, some of the most accurate sensors are presented. However, accuracy is not necessary the most crucial parameter for a sea mine. More important may be high resolution, usually given as a percentage of the full-scale pressure range.

Another factor is the choice of material for the “wetted part” of the sensor. The part of the pressure sensor that is exposed to seawater has to be able to withstand this highly corrosive environment without being damaged. Most sensors use stainless steel grade 304 or 316 in their wetted parts. This is not necessarily good enough. Stainless steel grade 316 is the standard molybdenum-bearing grade or “marine grade stainless steel”. The molybdenum gives 316 better overall corrosion resistant properties than grade 304, particularly higher resistance to pitting and crevice corrosion in chloride environments, but it is not resistant to warm seawater. In many marine environments 316 does exhibit surface corrosion, usually visible as brown staining. This is particularly associated with crevices and rough surface finish. Thus, other materials, like titanium or duplex (ferritic/austenitic) stainless steel, would make a better choice for underwater pressure sensing elements. However, for an expendable sea mine this might be of lesser importance.

8 ACOUSTIC SENSORS

8.1 Introduction

The acoustic signature originates from vibrating machinery, the ship’s structure and plates, the propellers churning the water, and the flow of water along the hull. Level reduction, termed *quietening*, is possible by identifying and damping the sources of the vibrations and, in many cases, by reducing speed. Measurements of the radiated underwater noise are made by *noise ranging*, whereby a ship is run in known machinery states and at constant speeds and aspects past measurement hydrophones.

The background ambient noise is dominated primarily by the contributions from merchant shipping and from wind, but the level of noise originating from seismic and volcanic activity can be considerable, at least in some parts of the world. Background noise can travel very long distances under water and can mask a ship's signature. The temporal characteristics vary widely, from very short, high-level "impulse" events to lower level "rumblings" lasting several days.

Underwater acoustic transmission losses are geographically dependent, being a function of the sound speed profile, the bathymetry, and the geo-acoustic properties of the sea floor along the transmission path. At the sensor, the dynamic range span required to encompass the signals from passing ships and the wide diversity in the natural background noise, can exceed 140 dB.

8.2 Physical principle

A hydrophone is a passive listening device used to detect relatively low frequency (<100 kHz) noise under water. The state of stress is considered effectively hydrostatic, as the wavelengths of sounds in this frequency range are much larger than the transducer dimensions. The voltage produced under hydrostatic pressure is used to measure the sensitivity of a hydrophone. (9) The active transduction element is usually made of a piezoelectric or electrostrictive material although fibre optic hydrophone systems are becoming more available at least in larger hydrophone arrays for the oil-industry.

Piezoelectric ceramic sensors:
After the discovery of ferro-electricity in $BaTiO_3$ ceramics in the 1940s in various parts of the world independently, a large array of ceramic ferroelectric materials has been developed. Especially, PZT, a binary solid solution of lead zirconate (PZ), and lead titanate (PT) has found widespread use because of its outstanding piezoelectric properties. A number of single crystal materials, including quartz (SiO_2), also exhibit piezoelectricity. (9)

Piezoelectric polymer sensors:
Piezoelectric polymer sensing elements consist of polarized polymer film that is stretched over and attached to a supporting frame or spool (mandrel).

The piezoelectric behaviour of polymers was first reported in 1969. The behaviour results from the crystalline regions formed in these polymers during solidification from the melt. The most widely known piezoelectric polymers are polyvinylidene fluoride, also known as PVDF. (9)

Piezoelectric ceramic/polymer composites:
Piezoelectric composite sensing elements consist of piezoelectric ceramic particles or fibres combined with an electrically insulating, acoustically transparent rubber, polymer or epoxy compound, where the compound is an integral part of the sensing elements.

Ceramics are less expensive and easier to fabricate than polymers or single crystals. They also have relatively high dielectric constants and good electromechanical coupling. However, they have high acoustic impedance, and, therefore, are a poor acoustic match to water, the media through which it is typically transmitting or receiving a signal. Also, because they are stiff and brittle, monolithic ceramics cannot be formed onto curved surfaces, limiting design flexibility in the transducer. They also have a high degree of noise associated with their resonant modes.

Piezoelectric polymers are acoustically well matched to water. They are also very flexible and have few spurious modes. However, applications for these polymers are limited because of their low electromechanical coupling, low dielectric constant, and high cost of fabrication.

Piezoelectric ceramic/polymer composites have shown superior properties when compared to single-phase materials. They combine high coupling, low impedance, few spurious modes, and an intermediate dielectric constant. In addition, they are flexible and moderately priced. (9)

Optical fibre sensors:
Various optical fibre methods of sound detection exist. Intrinsic optical fibre sound sensors configure a length of the optical fibre itself as the acoustically sensitive element and employ interferometric or polarimetric methods or in-fibre Bragg gratings to detect acoustically induced strains within the fibre itself. To obtain adequate sensitivity, a long fibre interaction length is required, perhaps by winding the fibre into a coil.

In extrinsic optical fibre sensors, the fibre is used to deliver light to and from an optical sensor at the end of the fibre. Because the lateral dimensions of the optically sensitive element are defined by the spot size of the incident illumination, very small element sizes, down to the optical diffraction limit of a few microns can, in principle, be achieved. (8)

8.3 Sensor examples

8.3.1 Reson A/S

- Reson's precision reference hydrophones are designed for meticulous underwater acoustic measurements and signal detection and / or calibrated reference acoustic projection.
- The base material of RESON hydrophones is "Sea Bronze" (an aluminium bronze alloy, $ALCu_{10}Ni_5Fe_4$). It has a better corrosion resistance over time than Stainless Steel.
- The special formulated NBR rubber has replaced chloroprene for the RESON hydrophones without any change in performance specifications and physical outlines. The NBR rubber encapsulation has very good chemical resistance to hydrocarbons and other pollutants likely to be found in harbours. It is also well suited for applications directly submerged in fluids such as kerosene and castor oil. However, NBR show some sensitivity to UV and Ozone, and care should therefore be taken not to expose the hydrophones to direct sunlight and weathering for very long periods.

Model	Description	Frequency (kHz)	Receiving Response (dB)	Operating Depth
TC4013	Miniature Reference Hydrophone	1Hz - 170kHz	- 211dB ±3dB	700m
TC4014	Broad Band Spherical Hydrophone with Built-in 26dB Preamplifier	15Hz - 480kHz	- 187dB at 250Hz	900m
TC4032	Low Noise Sea-State Zero Hydrophone with Built-in 10dB Preamplifier	5Hz - 120kHz	- 170dB at 250Hz	600m
TC4033	Robust Spherical Reference Hydrophone	1Hz - 160kHz	- 203dB ±3dB at 250Hz	900m
TC4034	Ultra Broad-band Spherical Reference Hydrophone	1Hz - 470kHz	- 218dB ±3dB at 250Hz	900m
TC4035	Broad Band Miniature Probe Hydrophone with Built-in 10dB Preamplifier	10kHz - 1MHz (down to 1Hz if SPL > self noise)	- 214dB ±2dB at 100kHz	300m
TC4037	Spherical Reference Hydrophone for High Pressure	1Hz - 100kHz	- 193dB at 250Hz	1500m
TC4038	Broad Band Miniature Probe Hydrophone	10kHz - 1MHz	- 227dB ±2dB at 100kHz	20m
TC4040	Reference Hydrophone	1Hz - 120kHz +2-10dB	- 205dB	400m
TC4042	Low-Noise Spherical Hydrophone with 20 dB Preamplifier. Single or Differential output.	5Hz - 85kHz	- 173dB at 250Hz	1000m
TC4043	Miniature Hydrophone with Built-in 10dB Preamplifier	2Hz - 160kHz	- 201dB	700m
TC4050	Miniature Flush-Mounted Probe Hydrophone	0.3Hz - 100kHz	- 216dB ±2dB (15.8V/µPa)	400m

TC4032 *TC4033* *TC4043* *TC4050*

Figure 8.1 Hydrophones from Reson A/S.

TC4032:

Usable frequency range: 5Hz to120kHz.

Linear frequency range: 15Hz to 40kHz: ±2dB, 10Hz to 80kHz: ±2.5dB.

Receiving sensitivity: -170dB re 1V/mPa.

Horizontal directivity: Omnidirectional ±2dB at 100kHz.

Vertical directivity: 270° ±2dB at 15kHz.

Operating depth: 600m.
Survival depth: 700m.
Operating temperature range: -2°C to +55°C.
Storage temperature range: -30°C to +70°C.
Weight in air: 720g without cable.
Preamplifier gain: 10dB.
Max output voltage: 3.5Vrms at 12VDC.
Supply voltage: 12 to 24VDC.
High pass filter: 7Hz, -3dB.
Quiescent supply current: ≤19mA at 12VDC, ≤22mA at 24VDC.

TC4033:
Usable frequency range: 1Hz to 140kHz.
Linear frequency range: 1Hz to 80kHz.
Receiving sensitivity: -203dB ±2dB re 1V/μPa at 250Hz.
Transmitting sensitivity: 144dB ±2dB re 1μPa/V at 1m at 100kHz.
Horizontal directivity: Omnidirectional ±2dB at 100kHz.
Vertical Directivity: 270°±2dB at 100kHz.
Nominal capacitance: 7,8 nF (incl.10m cable).
Operating depth: 900m.
Operating temperature range: -2°C to +80°C.
Storage temperature range: -40°C to +80°C.
Weight incl. 10m cable (in air): 1.5kg.

TC4043:
Receiving sensitivity: -201dB re 1V/uPa ±2dB (at 250Hz typical).
Useable frequency range: 2Hz to 160kHz.
Linear frequency range: ±3dB 2 Hz to 80kHz.
Horizontal directivity pattern: Omnidirectional ±2dB at 100kHz 360°.
Vertical directivity pattern: ±2dB at 100kHz 0 ±165°.
Max operating depth: 700m.
Survival depth: 800m.
Operating temperature range: -2°to +50°C.
Storage temperature range: -30°to +70°C.
Supply voltage: 10 to 18VDC (nominal 12VDC).
Max output voltage: 1Vrms.
Output drive capability: 100m cable.
Insert voltage: 2Vrms (calibration signal recommended).
Insert attenuation: 30dB.
Quiescent current: 15mA at 12VDC.
Housing material: Stainless steel, AISI 316.

TC4050:
Usable frequency range: 0.3Hz to 100kHz.
Linear frequency range: 0.3Hz to 40kHz ±5dB.
Receiving sensitivity, nominal: -217dB re 1V/μPa.

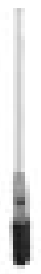
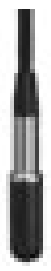
Horizontal directivity, pattern: Omnidirectional ±2dB at 20kHz.
Vertical directivity, pattern: 180° ±2dB at 25kHz.
Nominal capacitance: 2.45nF (1.45nF) (end of cable - sensor).
Charge sensitivity: 0.04pC/Pa.
Operating pressure: 0.05bar to 40bar.
Survival pressure: 40bar.
Operating temperature range: -2°C to +80°C.
Storage temperature range: -40°C to +80°C.
Rise time: 5µsec.
Weight (in air): 700g.
Housing material: SS AISI 316.
Leakage resistance: ≥2GOhms.
Equivalent noise pressure level: 64dB re 1µPa/√Hz at 1kHz.

8.3.2 Brüel & Kjær

The Brüel & Kjær range of hydrophones is a range of individually calibrated, waterborne-sound transducers that have a flat frequency response and are omnidirectional over a wide frequency range. Their construction is such that they are waterproof and have good corrosion resistance. There are four types.

- Type 8103 is suitable for laboratory and industrial use and particularly for the acoustic study of marine animals or for cavitation measurements.
- Type 8104 is ideal for calibration purposes.
- Type 8105 is a robust, spherical hydrophone that can be used at an ocean depth of 1000 m. It has excellent directional characteristics, being omnidirectional over 270 in the axial plane and 360 in the radial plane.
- Type 8106 has a built-in amplifier that gives a signal suitable for transmission over long underwater cables. It can be used down to an ocean depth of 1000 m.

Figure 8.2 Hydrophones from Brüel & Kjær.

Product Type	**8103**	**8104**	**8105**	**8106**
Voltage Sensitivity (w/cable) at 20 deg C	30µV/Pa ±8µV (-211dB re 1 V/µPa ±2 dB)	56µV/Pa ±15µV (-205 dB re 1 V/µPa ±2 dB)		2000µV/Pa ±500µV (-174dB re 1V/ µPa ±3 dB)
Charge Sensitivity	0.12 pC/Pa	0.44 pC/Pa	0.42 pC/Pa	-
Capacitance (w/cable)	3850 pF	7800 pF	7500 pF	-
Frequency Range (re 250 Hz)	(+1.5dB) 0.1Hz to 100kHz (-6.0 dB) (+3.5dB) 0.1Hz to 180kHz (-12.5 dB)	(±4.0dB) 0.1Hz to 80kHz (+4.0dB) 0.1Hz to 120kHz (-12.0 dB)	(+1.0dB) 0.1Hz to 100kHz (-6.5 dB) (+3.5dB) 0.1Hz to 160kHz (-10 .0dB)	(+0.5dB) 10Hz to 10kHz (-3.0dB) (+0.5dB) 7Hz to 30kHz (-8.0dB)
Operating Temperature Range Short-term /Continuous	-40°C to +120°C -40°C to +80°C			-10°C to +60°C
Max Operating Static Pressure	252dB = 4x10^6 Pa = 40 atm. = 400 m ocean depth		260dB = 9.8x10^6 Pa = 100 atm. = 1000 m ocean depth	260dB = 9.8x10^6 Pa = 100 atm. = 1000 m ocean depth
Dimensions: Length/ Body Diameter	50 mm (1.97”) 9.5 mm (0.37”)	120 mm (4.73”) 21 mm (0.83”)	93 mm (3.66”) 22 mm (0.87”)	182 mm (7.17”) 32 mm (1.26”)
Weight (Including Integral Cable)	170 g (0.37 lb)	1.6 kg (3.5 lb)		382 g (0.84 lb)
Integral Cable	6 m waterproof low-noise double-shielded Teflon cable with standard miniature coaxial plug	10 m water blocked low-noise shielded cable to MIL-C-915 with BNC plug		None

8.3.3 Engineering Acoustics, Inc.

- The **Model TH608** series hydrophones incorporate a piezoelectric ceramic sensor and a low noise preamplifier to achieve a wide dynamic range with excellent signal-to-noise performance. The TH608S model utilizes a cylindrical sensor, suitable for general applications, while the TH608Q model incorporates a spherical sensor for extended frequency response and greater pressure tolerance. Both models feature an integral preamplifier providing a voltage mode output capable of driving a minimum of 500 feet of cable. The voltage-mode output is readily compatible with a wide variety of off-the-shelf processing and acquisition systems. The assembly is encapsulated in a durable polyurethane and includes a hard cast polyurethane bulkhead which accommodates the underwater connector. All components exposed to the environment are constructed of non-metallic materials to provide long-term field service. The TH608 includes a calibration signal input, which allows in-situ testing of the sensor and preamplifier.
- **Model E100A** is a low cost, high reliability hydrophone well suited for buoyed and vertical arrays. 5Hz-5 kHz with integral current mode pre-amp. It has dual sensitivity, selectable by changing polarity of power supply. In addition, it is closely matched unit-to-unit amplitude and phase response.
- **Model E200** is a very low noise hydrophone. Its integral pre-amp is good to 1000 feet with less than 1 dB change in sensitivity. It is an excellent wide band (5Hz to 25 kHz), low noise hydrophone for noise measurement or receive applications.
- The **Model 93-BL** hydrophone is a dual-sensitivity, battery operated hydrophone designed for reliable operation in the harsh marine environment. The dual preamplifiers and standard 9V battery are contained in a cylindrical stainless-steel housing, and the ceramic sensor is encapsulated in a low permeability epoxy matrix. A stainless-steel bulkhead connector with o-ring face and crush seals are used to ensure watertight integrity. The end-cap bulkhead uses redundant radial o-ring seals for additional reliability. The modular design allows easy access to the preamplifier circuit board and battery. The Model 93-BL is designed to withstand multiple deployments and shipboard handling typical in marine geophysical operations. The responses curve of the 93-BL shows little variation with changing pressure.

TH608 *E100A* *E200* *93-BL*

Figure 8.3 Hydrophones from Engineering Acoustics, Inc.

TH608 Series Hydrophone:

	TH608S	**TH608Q**
FrequencyrRange	10 Hz to 40 kHz	10 Hz to 120 kHz
Flatness	Output Sensitivity +/- 2.0 dB between 100 Hz and 40 kHz	
Sensitivity	-160 dB re 1V/µPa	-180 dB re 1V/µPa
Preamplifier	Low Noise Voltage Mode	
Directivity	Omnidirectional, except within 30 degrees of connector	
Overload	160 dB re 1 µPa	190 dB re 1 µPa
Self noise level	Sea state 1 or less, equivalent noise pressure	
Maximum operating depth	500m	1000m
Supply voltage	24 +/- 4 volts DC	
Connector	LSG-3-BCL (1)	RMG-3-MP Pigtail (1)
Pin-out / signal	Pin 1 Signal Pin 3 Ground Pin 2 +24 VDC Pin 4 Calibration input	

Model E100A Hydrophone:

Free-field voltage sensitivity	-176 dB re 1 V/µPa (160 V/bar) in high sensitivity mode into a 1400 ohm sense resistor Sensitivity reduction of 40 ±0.5 dB in low sensitivity mode	
Frequency response	Flat to within 1 dB from 5 Hz to 2 kHz; within 3 dB to 5 kHz	
Peak pressure signal	+225 dB re 1 µPa in low sensitivity mode +185 dB re 1 µPa in high sensitivity mode	
Overload recovery	<= 50 msec after exposure to +240 dB re 1 µPa in low sensitivity mode	
Directivity	Omnidirectional within 1 dB (all planes) 10 Hz to 2 kHz Omnidirectional in horizontal plane within 1 dB to 30 kHz	
Depth range	0 to 1 km	
Unit-to-unit variability	±1 dB sensitivity; ±5° phase from 20 Hz to 2 kHz	
Equivalent noise pressure	20 Hz	+52 dB re 1 µPa per root Hz
(high sensitivity mode)	50 Hz	+50

	100 Hz	+39
	200 Hz	+37
	500 Hz	+35
	1000 Hz	+34
Supply	18 to 28 Vdc at 7 ma nominal (10 ma max)	
Sensitivity selection	Reverse polarity of supply voltage to select sensitivity	
Preamplifier calibration	Optional two separate leads to inject a calibration signal into a 10 ohm resistor between the sensor return and circuit common	
Connector(s)	Two RMA single-pin connectors (or equivalent) on 6" pigtail leads, colour banded for ID (+ power-red, - power-blue)	
Size	1.0 in OD x 6.0 inches long	

Model E200 Hydrophone:

Sensitivity into 220 ohm source resistor	-178.0 dB re 1 µPa/V at 1 kHz (male positive pin)
Pass band flatness	+/- 1 dB over 20 Hz to 5 kHz +/- 2 dB over 5 kHz to 25 kHz
Max. linear output	2.0 Vrms with < 2.0% distortion
Max. operating depth	1000 meters
Operating temperature	-5 to 35°C
Max. sensitivity change	+/- 1 dB max. with depth 0 to 1 km +/- 2 dB max. with temperature 5 to 35°C
Directivity	Omnidirectional within +/- 30 degrees of a plane perpendicular to the sensor axis
Nominal current draw	10 mA with 18 to 24 Vdc supply
Noise performance	Lower than sea state zero from 20 Hz to 25 kHz
Connector	SeaCon MAW-2-HC (1)
Size	1.5" OD x 4.0" length

Model 93-BL Hydrophone:

Frequency range	1 to 1500 Hz +/- 1 dB	
Directional response	Omnidirectional	
Sensitivity	Dual 1 V/bar and 10 V/bar std. (1)	
Maximum depth	3000 Ft	
Noise	Freq.(Hz)	dB re 1µPa/sqrt(Hz)
(10 V/bar range)	20	+62
	50	+60
	100	+58
	500	+57
	1000	+57
Peak pressure	2 bar operational on 1 V/bar sensitivity 10 bar non-operational with 100 ms recovery time	
Battery	NEDA 1604A, 9 V Alkaline	
Battery life	> 1 year	
Connector	4 pin, AG Geophysical 2704M (2)	
Materials	304SS, Epoxy Encapsulant	
Size	7.25" x 2.0" diameter	

8.4 Recommendation

Although different technologies exist, the piezoelectric ceramic hydrophones are seemingly still the most popular type. It is therefore likely that these will be used in sea mines.

The mechanical arrangement should be such that the hydrophone is protected against fishing operations such as trawling, and at the same time have a clear acoustic pathway to the surface. The shape and size of the hydrophone's casing is an important factor in this regard.

References

(1) Steven A. Macintyre (1999): The Measurement, Instrumentation and Sensors Handbook In: chapter 48: Magnetic Field Measurement (Eds John G. Webster), CRC Press LLC, USA.

(2) John S. Kay (1997): Equipment development for the measurement of underwater multi-influence fields, *IPENZ Transactions* 24, 1/GEN.

(3) Anders Lundin (2003): Swedish National Defence College. THESIS: Underwater electric signatures. Are they important for a future navy?

(4) Jens Havskov and Gerardo Alguacil (preliminary version, June 2002): Instrumentation in Earthquake Seismology.

(5) Jens Havskov (2004): Overview of Seismic Instruments, Workshop, High Quality Seismic Stations and Networks for Small Budgets, Volcan, Panama, 8-13. March.

(6) Christophe Lemaire, Business Development Engineer, Analog Devices (): Low-Cost, iMEMS® Accelerometers Sense Strong Motion Seismic Activity for Hazard Mitigation Applications.

(7) Robert E. Bicking (1998): Fundamentals of Pressure Sensor Technology, Sensors, Vol 30.

(8) Paul C. Beard, Andrew M. Hurrell and Tim N. Mills (January 2000): Characterization of a Polymer Film Optical Fiber Hydrophone for Use in the Range 1 to 20 MHz: A Comparison with PVDF Needle and Membrane Hydrophones, *IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL: VOL. 47, NO. 1, JANUARY 2000.*

(9) E. Koray Akdogan, Mehdi Allahverdi, and Ahmad Safari (May 2005): Piezoelectric Composites for Sensor and Actuator Applications, *IEEE transactions on ultrasonics, ferroelectrics, and frequency control.*

(10) USA Department of Defence (August 2003): Military Critical Technologies List, Section 16.4, Magnetic and Electromagnetic Sensor Systems.

(11) James Lenz and Alan S. Edelstein (June 2006): Magnetic Sensors and Their Applications, *IEEE Sensors Journal, vol. 6, no. 3.*

(12) Alan Washburn (16 December 2005): Mine Warfare Models, Naval Postgraduate School.

(13) Lennart Crona and Anders Brage: Carbon Fibre Electrodes and their Qualities in Salt Water.