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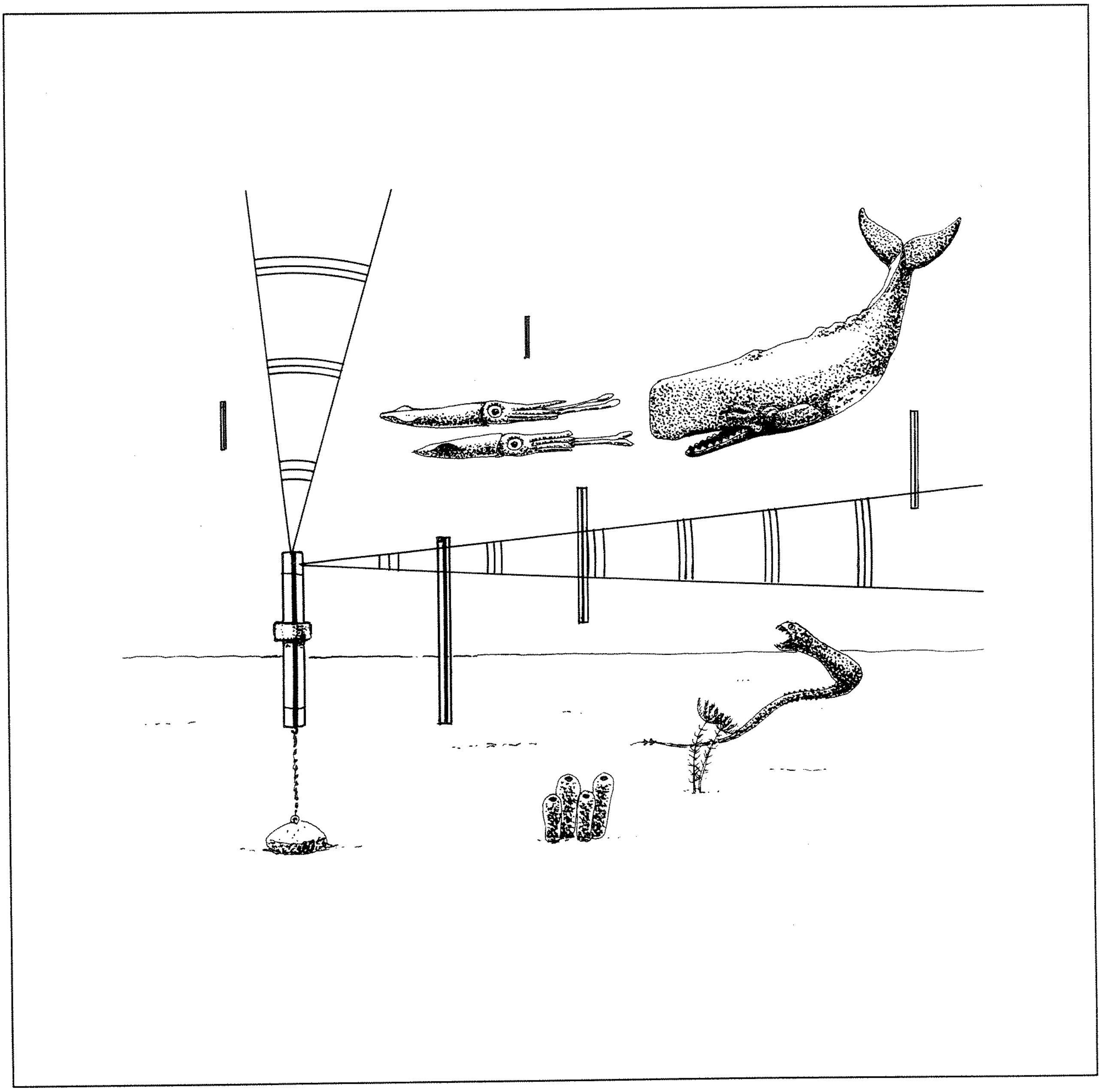
Acoustically tracked passive drifters for measurement of oceanic circulation

Adaptation to the Nordic Seas



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Abstract:

A review of the technology to use neutrally buoyant subsurface drifters or floats for Lagrangian measurements of ocean circulation was made. Focus was put on the RAFOS technology which uses small floats that listen to low-frequency sound-transmitting sources moored at fixed positions in the deep water. Recent applications of this and similar techniques have been studied. Some suggestions for future float applications with emphasis on studies in Nordic waters are presented. These include measurement of the internal circulation in the deep basins, and the exchange of waters between them. The float technology requires close follow-up during planning and execution of experiments by the scientists involved. It is recommended in the beginning to spend most efforts on tasks related to scientific planning and performance, and less on the technological parts, by applying as much commercially available equipment as possible.

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For the Administration

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Acoustically tracked

passive drifters for measurement of oceanic circulation.

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Bergen, Norway, November 1995

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PREFACE

Sophisticated neutrally floating drifters have been used by several oceanographic institutions in circulation studies since the 1950's. Both the technology and the techniques for applying the drifters have undergone significant extensions and improvements. The technology has so far been used only by a limited number of institutions, mainly in the USA

NIVA and others considered that the drifter technology also might be used by other countries and in new oceanic regions such as in the Nordic seas. The Nordic Council found that the idea to perform an evaluation study on this topic was fruitful, and provided funding for the present study through the project Measurements and Modelling (grant No. 7.06, 1994). NIVA supported the project through grant # E-94410.

Dr. Henrik Søiland already had experience from using RAFOS drifters in the USA The study included a visit in 1994 to the University of Rhode Island and Prof. Tom Rossby and Jim Fontaine, from whom we acknowledge the support and numerous ideas.

We also visited the manufacturers of drifters Bathy Systems Inc. and Seascan, and the sound source producer Webb Research Corp. in Massachusetts, and received valuable information from them. Amy Bower and her colleagues at Woods Hole gave us a valuable update on their experiences and developments.

Bergen, Norway
November 1995

Lars G. Golmen *Henrik Søiland*

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SUMMARY

Neutrally buoyant, subsurface drifters or floats that are positioned underway in the deep ocean by means of acoustic signals from fixed sound sources have become widely used by several oceanographic institutions around the world.

These subsurface floats are prepared to be deployed from ships and sink to a predetermined pressure or density surface, for then to drift passively with the current at this pressure or density until they automatically ascend to the surface after several months and report all its recorded data to shore via satellite. In this way, the paths of the deep water flows and the variability of measured environmental parameters underway may be determined. This Lagrangian method to measure deep currents enables many scales of circulation, including eddies, to be resolved and is thus in many instances superior to traditional measurements made at fixed mooring positions.

So far, experiments with such subsurface drifters have been conducted only by the some leading nations such as the USA, Germany, France and UK. Despite the promising nature of this technology, it has yet to be adapted by Nordic oceanographic institutions, and only a very few limited experiments have been performed in the Nordic water domain.

On contract from the Nordic Council, NIVA, the Norwegian Institute for Water Research in 1994 was funded to review the technology and its various applications. Suggestions should be made for topics for future experiments in Nordic waters, which should have significant involvement from Nordic oceanographers, with the long term goal to establish one or more independent regional user groups.

The report reviews the historical development, and describes in more detail the RAFOS float which has been the most commonly used in recent years. New float versions are being developed, including multi-cycling floats that ascend to the surface many times during their missions to report stored data via satellite before descending again. These versions may operate without acoustic positioning, relying only on satellite position fixes while on the surface.

The post-processing of sound signal data received by the float to compute the track requires some manual editing and control and correction for drift in clocks. Except for this, the data presentation and many forms for analyses may be computerized.

In the Nordic Seas many scientific issues may be clarified by use of subsurface floats. These relate to the exchange of deep and intermediate water internally and with adjacent seas, and to the internal circulation pattern and their variability in space and time.

The physical transformation of water masses and the transport and dispersion of pollutants within and between the deep basins may be explained much better than with traditional measurement methods. Biological factors such as drift patterns of zooplankton, pelagic fish eggs and larvae which are thought to be strictly coupled to the circulation may be better explained by using deep, Lagrangian drifters.

The hydrographic conditions for sound propagation in parts of the Nordic Seas and in enclosed water bodies such as the Baltic and fjords are not as optimal for long range tracking as in open oceans with a deep sound velocity minimum. But by adapting and applying new technologies together with sensors for measuring chemical parameters, carefully designed experiments are predicted to give valuable new insights into the patterns of deep and intermediate water currents, and data on physical, chemical and biological processes within these waters.

1. INTRODUCTION

1.1. Background and purpose of the report

The most common method to measure water currents is to deploy self-contained recorders for a period of time at fixed positions and depths (fixed moorings). This "Eulerian" method describes the current in one particular position. By combining measurements at several locations at the same time, one will get a picture of the spatial current distribution. This, however, will often require substantial effort and cost.

A different method which is dealt with in this report, is to measure the path of the water "parcels" by means of neutrally buoyant subsurface dirfters or floats. This "Lagrangian" approach is very useful in environmental studies such as of dispersion and dilution phenomena, eddies and whirls of different scales in the ocean etc. Fig. 1 shows an example of a float trajectory from deep within the Gulf Stream.

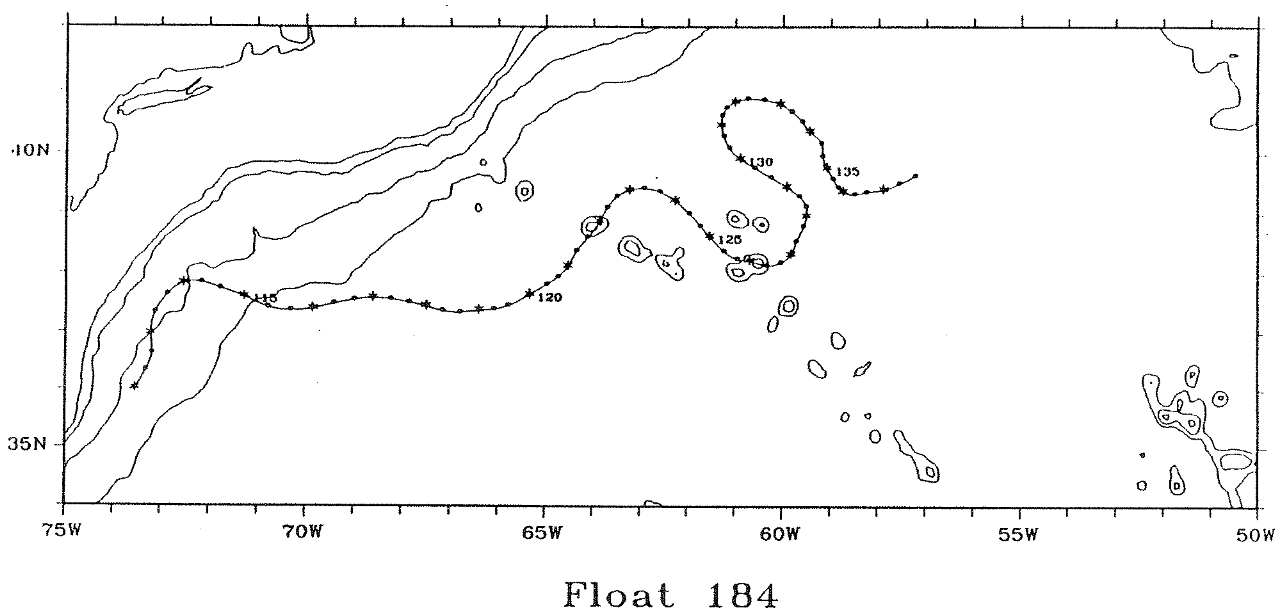


Fig. 1. Lagrangian float trajectories from the Gulf Stream. The depth of the float varied between 300 and 600 m. Position every 24 h is denoted by a star. From Anderson-Fontana and Rossby, (1991).

Lagrangian measurement methods are constantly being upgraded, from past times surface drogues till today's acoustically tracked deep water passive drifters, which now is commercially available at moderate cost.

Despite the usefulness of the neutrally buoyant, subsurface floats for measuring deep currents, it is not as commonly used as Eulerian measurements. Application of the sophisticated float technology has been restricted to a limited number of highly specialized labs and institutions, mostly in the USA. Among European countries, France has been leading, with a few others (Germany, England, Italy) coming up. So far, no Nordic user groups or institutes exist.

The purpose of the present study is mainly to review the development of the Lagrangian drifter technology, and describe its present state. Furthermore the potential for future applications within the "Nordic Seas" is studied. The possibilities for transfer of technical know-how to Nordic communities are briefly evaluated.

More specifically the study has sought to clarify the following questions:

- ***In which types of studies are the passive drifter technology superior to traditional fixed position measurements?***

- ***What distinguishes the different subsurface drifter techniques presently used?***

- ***What may be the challenges and benefits by using passive drifters in Nordic oceanography?***

According to the scope of the work for the study, a brief description of the sub-surface passive drifter technology is made, including a presentation of the historic path leading onto the present sophisticated devices. Some suggestions are made for future experiments and developments.

The study focuses on drifters or floats with underwater acoustic tracking for positioning. Modes of operation involve powerful low-frequency sound sources, and ditto receivers. Floats may either receive or send signals, according to type.

Passive drifters are most commonly known in the form of surface drogue types, i.e. with surface markers carrying near-surface drogues or parachutes (Pickard and Emery 1986, p. 81). Even simpler methods such as drift bottles of sheets of paper are still used to track surface currents.

High resolution Lagrangian current measurements with radio technology began in the 1970's, with small radio transmitters. The economical surface "Davies" drifter made by Davies and others (Davies et al. 1982) was since used by many investigators.

The surface drifter may communicate its position and measurement data to shore via VHF or ARGOS. Positions may be acquired by LORAN or GPS (Wilson 1992). Position may also be determined acoustically for surface drifters using high frequency (8-11 kHz) transponders (McKeown 1989). Water sampling and measurement gear at different depths may be suspended from the surface buoy. The sampling equipment may include thermistor chains, CTDs, optical sensors and automated water samplers (see e.g. Abbot et al. 1990 for a description of a recent experiment).

Sea bed drifters (SBD) have been used for decades to study benthic boundary currents and sediment transport. These consist of a small weakly buoyant parachute with a small ballasted tail that make the SBD gently drag along the bottom. SBD recovery is based on a voluntary reporting by the finders, like fishermen or divers. The percentage of SBD's returned in numerous experiments around the world including the North Sea varies from 2 to 80 (Resio and Hands 1994).

1.2. Sub-surface drifters

Sub-surface drifters, or floats, are the main topic of the present report. Common to most of these drifters are that they are made to drift neutrally at a pre-set pressure (or density surface) for long periods, and that they use sound pulses to fix their position or range relative to either sound sources or listening hydrophones. The various types that have been and are in use, are briefly described below.

SWALLOW FLOATS

The idea of using specially designed neutrally buoyant floats to measure deep oceanic currents was presented in a note by Henry Stommel in 1955 (Stommel 1955). The first floats were developed by Jim Swallow in the mid 1950's (Swallow 1955). These SWALLOW floats were two parallel 3 m long aluminium cylinders, each with slightly smaller compressibility than sea water. The sound generating devices regularly transmitted sound pulses that could be detected by hydrophones on listening ships, or other underwater receivers (Neuman and Pierson 1966, p. 108).

Douglas Webb at WHOI developed a spherical float in the 1960's that was particularly made for observing vertical convection (Webb and Worthington 1968). Fins were protruding from the equatorial periphery of the floats (Fig. 2). Float rotations from vertical currents were detected by sensors inside. The convection data often were masked by large vertical currents being caused by vertical oscillatory motions. Despite this, successful experiments were reported (Voorhis and Webb 1970).

SOFAR FLOATS

A further development of the SWALLOW float was the SOFAR technology with neutrally buoyant floats made from aluminium tubes (Fig. 3) or glass spheres. The name derives from the *sofar channel*, i.e. the deep layer on minimum sound velocity where sound may propagate very long distances (SOFAR: Sound Fixing And Ranging).

The SOFAR floats have been used in many studies from the first one in 1972 in MODE (Mid Ocean Dynamics Experiment, Rossby et al. 1975). The transmitted sound signals had a typical range of 1,000 km. In the follow-up POLYMODE experiment, a new float with improved signalling scheme with the range of 2,000 km was developed, and later used in the POLYMODE Local Dynamics Experiment (Rossby et al 1986).

Typical malfunctions of the early SOFAR floats was drift in the internal clock and plastic deformation of the aluminium hulls. The latter caused the floats to sink slowly from their target depth, and was later compensated for by a self-ballasting unit (Owens 1991). The time shift affected the determination of position, but this trouble could to a large extent be alleviated by carefully considering time data at three or more listening stations.

The early SOFAR floats were generally fixed once every day. The accuracy of each fix was about 5 km. But the relative error over periods of days to weeks was significantly better (Cheney et al. 1976).

With the development of Autonomous Listening Stations (ALS) in the late 1970's, listening stations no longer had to be deployed in the vicinity of islands or coasts. The ALS recorded the arrival times of float signals on magnetic tapes, which were processed after retrieval of the ALSs. This new technology largely widened the experimental range.

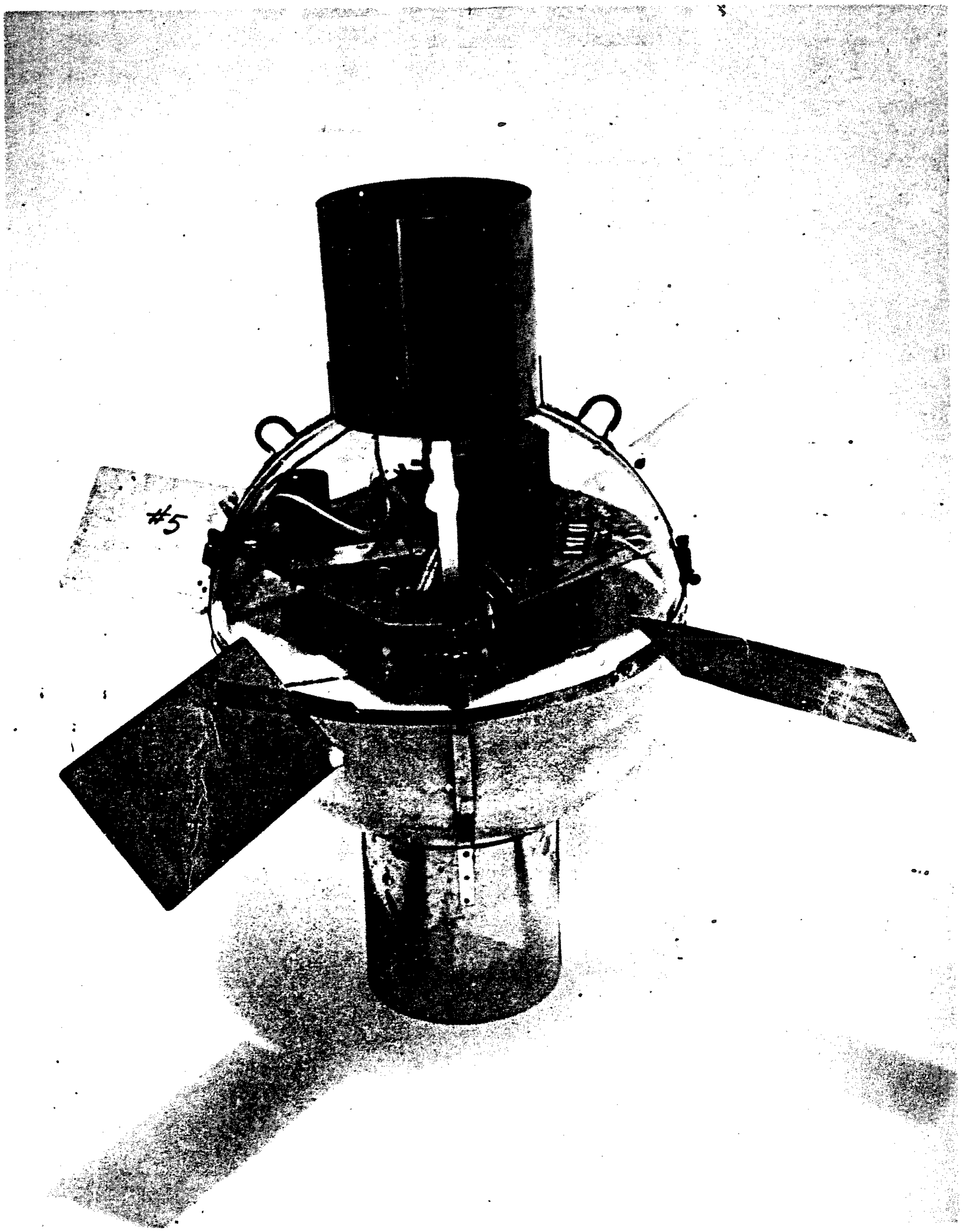


Fig. 2. A spherical "SOFAR" float made to measure vertical convection in the Mediterranean ca 1969.

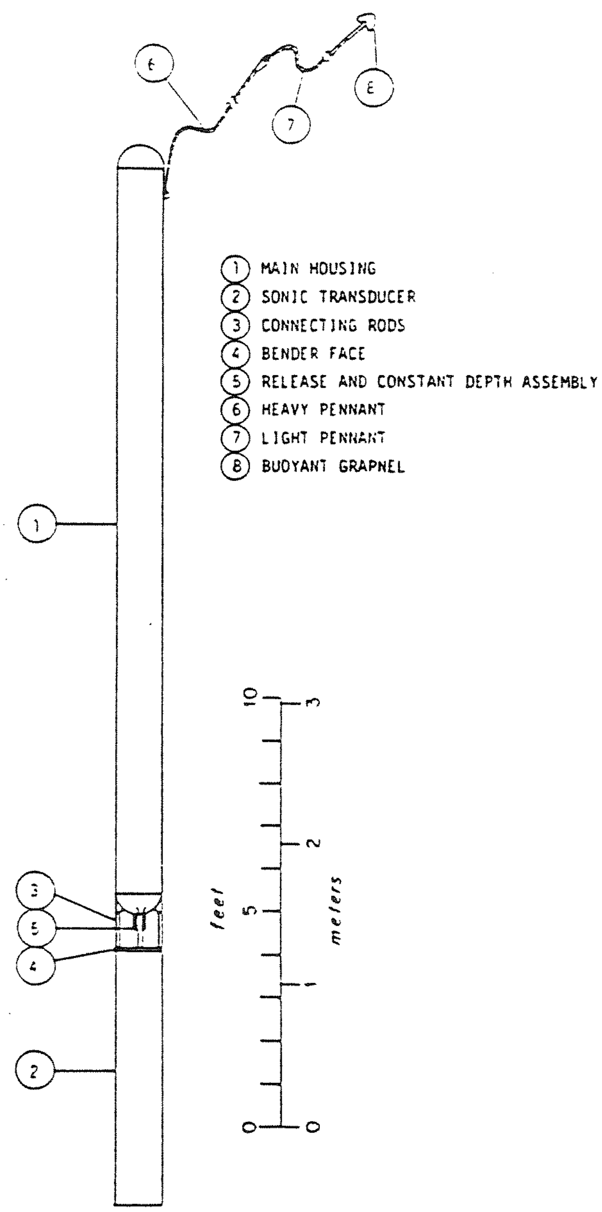


Fig. 3. Sketch of a temperate ocean SOFAR drifter (From Colony, 1986). The overall length is about 8 meters, with the sound transducer separated from the main housing, which contains batteries, electronics and buoyancy control.

RAFOS FLOATS

SOFAR floats were still transmitting sound, as the SWALLOW floats did. Deep anchored receivers (ALS) detected the pulses from the floats, and stored the ping data for later retrieval. The RAFOS (SOFAR spelled backwards) technology, developed by professor Tom Rossby at the University of Rhode Island in USA, listened and stored the signals from fixed sound sources, in stead of transmitting signals itself (Rossby et al., 1986). This implied a significant reduction both in physical dimensions and in manufacturing cost. RAFOS floats were first used in 1984-85 in the RAFOS Pilot Experiment Study in the Gulf Stream (Rossby 1987), and have later been used in several experiments both in the Pacific and the Atlantic Ocean.

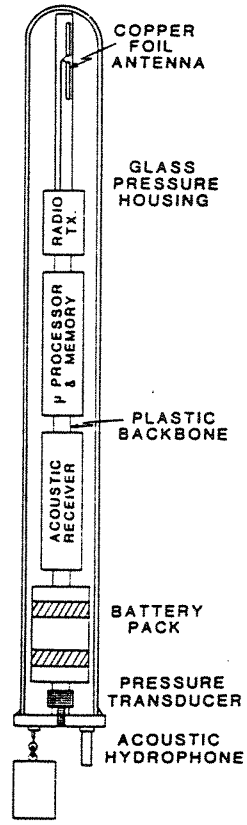


Fig. 4. The typical RAFOS glass-tube design (from Bower, 1984)

An updated version of the RAFOS float was developed in the late 1980's (Fig. 4). This version enabled more flexibility in setting (programming) mission parameters. In addition, the cost of manufacturing was significantly reduced. This RAFOS technology forms the basis for the present study. A review of recent developments is given by Bower (1994).

ALACE FLOATS

The Autonomous Lagrangian Circulation Explorer (ALACE) is a neutrally buoyant subsurface float which is able to ascend to the surface periodically, and report its position and environmental data via the ARGOS satellite system (Davis et al., 1992). It does not have to rely on any acoustic positioning. The ALACE float provides the submerged displacement between two trips to the surface and in addition pressure, temperature and also salinity measurements (profiles, Fig. 5). The ALACE float is housed in a ca 1 m long (+ 70 cm antenna) and 17 cm diameter aluminium tube and has a mass of 23 kg. See Fig. 6. The max. depth is 2,000 m.

The ALACE float is ballasted before launch and it is capable of changing the volume by inflating an external bladder with oil such that the float becomes buoyant at the surface. The floats are capable of 50-75 ascents to the surface, dependent on both batteries and depth. The period it stays down is programmable and in typical operation will be 20 to 30 days. The floats are thus designed to measure the large scale average flow, and not energetic mesoscale eddy activity. The ALACE is more expensive than the RAFOS float, but experimental cost is saved on sound sources. A redesign - ALACE-2 - which will have a reduced price, will probably be available early in 1997.

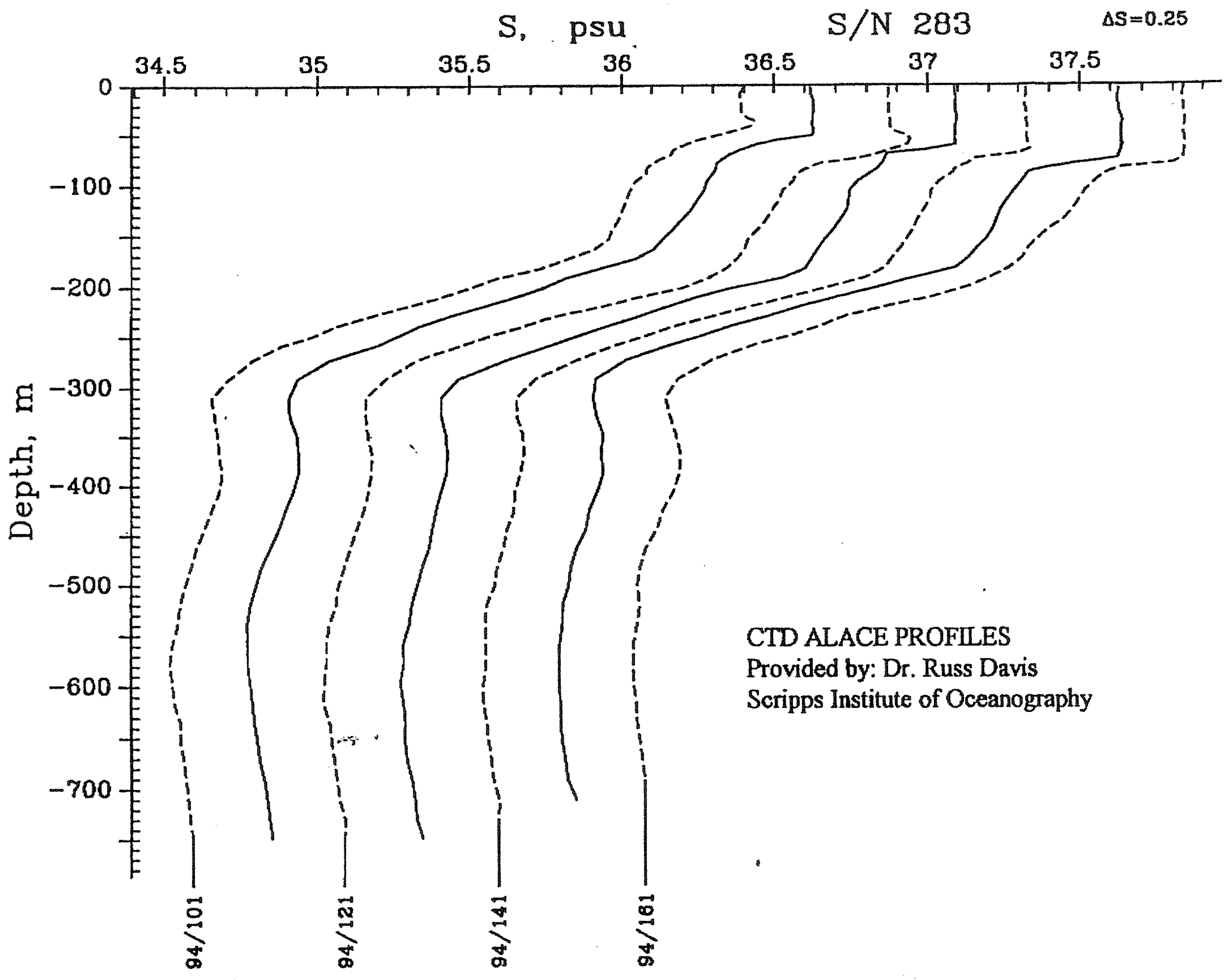


Fig. 5. Example of successive salinity profiles measured recently by a multi-cycling ALACE float in the Pacific. Courtesy of Russ Davis, Scripps Oceanographic Institution.

Between 300-400 ALACE floats had been deployed in the Pacific Ocean by the end of 1994. The ALACE float is manufactured by Webb Research Corp. in Massachusetts. By October 1995 more than 600 ALACEs have been built, mostly for the WOCE work of Russ Davis at Scripps (Daniel Webb, pers. comm).

Testing of a modified ALACE (ALACE-B) began in July 1995. This float or profiler is ment for shallower work (400 m or less), and will have the ability to surface about 150 times (perform 150 cycles). ALACE-Bs equipped with a fluorometer will also be deployed. A new 'Multi-Trip Profiler' that will be capable of 200 cycles to 200 m depth is being developed by Webb Research (Daniel Webb, pers. comm.). This may be launched and retrieved for battery recharging, applying GPS positioning and satellite or short-range RF modem.

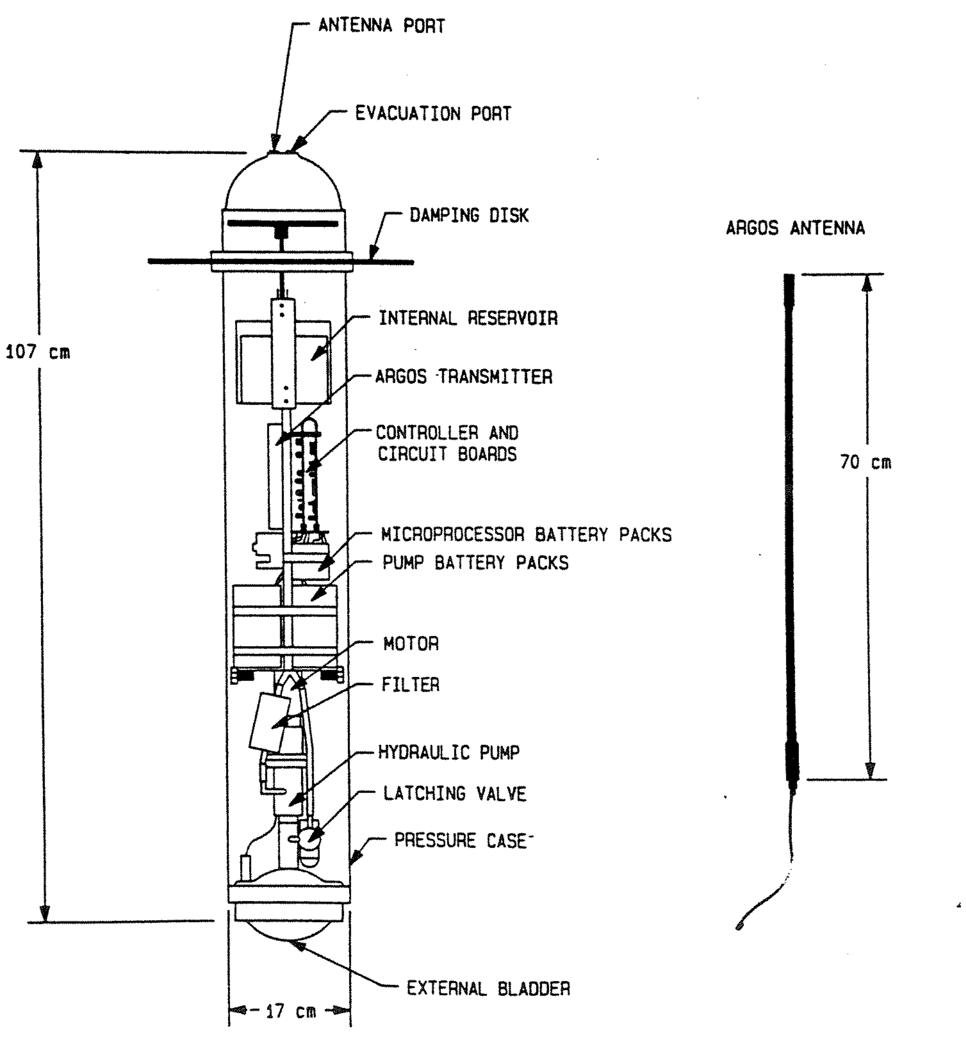


Fig. 6. Schematic of an ALACE (from Davis et al. 1992). To ascend, the hydraulic pump moves oil from the internal reservoir to the external bladder. To descend, the latching valve is opened allowing oil to flow back into the reservoir. The antenna shown to the right is mounted on top of the hemispherical endcap.

ALFOS and MARVOR FLOATS
These floats are both combinations of the principals of the RAFOS and ALACE floats. The ALFOS float is basically an ALACE float that has been equipped with the RAFOS electronics and is thus capable of listening to and store the acoustic signals in the same way as RAFOS floats. The ALFOS float has actually been used to monitor the sound sources during RAFOS experiments.

The MARVOR float which is manufactured by Tekelec in France is also fitted with an acoustic receiver and a hydraulic system to inflate/deflate an external bladder. It may thus ascend to the surface and report position and environmental data in the same way as the ALACE and ALFOS floats. It may be used together with standard Webb Research Corp. sound sources. The sensors of temperature and pressure and the acoustic receiver are made by Seascan. Battery capacity (theoretical) is for 3 years operation with periods of 8 hrs listening on-8 hrs listening off. It may be programmed to operate for several long periods at the target depth with short ascents in between to transmit accumulated data (Ollitraut et al. 1994).

The hydraulic system is constructed such that the MARVOR float is capable of controlling its depth by adjusting the volume of the bladder with small amounts. The MARVOR float thus does not require ballasting before launch. Since the MARVOR float is equipped with a hydrophone and electronics to detect acoustic signals from sound sources its tracking information is stored. In a typical mission with an acoustic fix every 8 hrs it may stay down for two months before it ascends to the surface to report its data. The MARVOR floats are designed for about 30 such descents/ascents to the surface.

THE KIEL - TIEFENDRIFTER
The 'Kiel-Tiefendrifter' is a multi-cycling float that is being developed by the Institute of Applied Physics in Kiel (Knutz et al. 1995). Developments started in 1989. Its special feature is the use of the orientation of the earth's magnetic field for subsurface tracking (a compass and a GEK system). It has many programming options, and is presently capable of 1,200 m depth.

2. HYDROACOUSTICS

2.1. Basics

Sound waves propagates in the ocean at a speed of about 1460 m/s for typical oceanic conditions. The speed of sound is functionally dependent on salinity, temperature and pressure (depth). This means that sound speed varies with depth as well as location. Typical variations are shown in Table 2.1 for oceanic conditions. The salinity effect in the open ocean is small, and is often neglected in acoustic studies. However, it must not be overlooked in areas with a strong halocline (e.g. fjords). The speed does not depend on frequency (non-dispersive conditions). The internationally accepted UNESCO equation for calculation of sound speed is listed in Appendix 1, in FORTRAN code, for reference.

At low and mid latitudes the typical hydrographic distribution with the decrease in temperature with depth causes sound speed to decrease from the surface down to a certain depth. From here the pressure effect dominates and causes a sound speed increase towards the bottom. Sound waves are refracted in the direction towards lower speed. Thus the intermediate layer of minimum sound speed that is formed at 500-1000 m depth, below the main thermocline, traps horizontally propagating sound waves, and enhances sound transmission range significantly. The layer of minimum sound speed is named the SOFAR channel.

Energy dissipation (absorption) increases as the square of the frequency. This favours the use of low frequency sound for long-range applications, such as float experiments and mapping of ocean temperature (the ATOC programme, conf. para. 4.2).

Different sound reference pressures are generally used in air and water. In air, the lower human listening threshold of 20mPa (at 1000Hz) is used. In water, the reference commonly used is 1 mPa, which shifts the two scales by 26 dB (20xlog(20) = 26), with the higher dB values in water. Besides having different reference levels, the impedances are different in air and water. Thus sources radiating the same pressure (per unit area) generate ca 5,000 times more power in air than in water.

Table 2.1. Typical variations of sound speed with hydrographic parameters.

Parameter increase	Sound speed increases
Temperature, + 1°C	ca 4 m/s
Salinity, + 1 p.p.t.	ca 1.5 m/s
Pressure, + 1000 db	ca 18 m/s

2.2. Sound propagation in high latitudes

The present study focuses on Arctic and sub-Arctic regions. The hydrographic conditions in these waters differ for the ones at lower latitudes. In general the variation in sound speed in these waters with very weak stratification, is dominated by the pressure effect and thus the sound speed minimum commonly is found near or at the surface. I.e. the sound waves refract towards the surface. During summer, the warm surface layer may still maintain a shallow intermediate layer of minimum sound speed, which favours horizontal sound transmission. Also the Arctic regions influenced by Atlantic Water inflow may have a subsurface speed minimum. Fig. 7 shows vertical sound speed profiles in the central Norwegian and Greenland seas and from the Fram Strait.

Coastal regions have different hydrographic characteristics compared to the open ocean. Bottom topography, hydrographic fronts, stratification and currents vary on short space/time scales. This is also reflected in rapidly changing sound propagation conditions. In semi-enclosed basins such as fjords sound waves will partly be reflected, and partly absorbed along the boundaries. This poses another set of difficulties when applying traditional sound ranging technology.

The sound speed in the Nordic Seas varies largely between 1,440 m/s (winter in the NW) to 1,500 m/s (SE regions during summer). Roughly the sound speed profiles may be grouped into three classes according to region (Hurdle, 1986):

1. Regions influenced by warm North Atlantic Water to the E and SE
2. The transition region between the previous region and the Arctic domain to the W and NW.
3. Regions dominated by cold water of Polar/Arctic origin.

The depth of the sound speed minimum varies accordingly to a large extent when crossing from one region to the other. Fig. 8 shows two W-E sections of sound speed. In the regions west of the Polar Ocean Front the speed minimum is always at or very close to the surface. Thus the Greenland Sea actually has its acoustic-channel axis at the surface. To the east, the speed minimum is at 500-800 m depth in the Norwegian Basin and at 900-1,200 m depth in the Lofoten Basin.

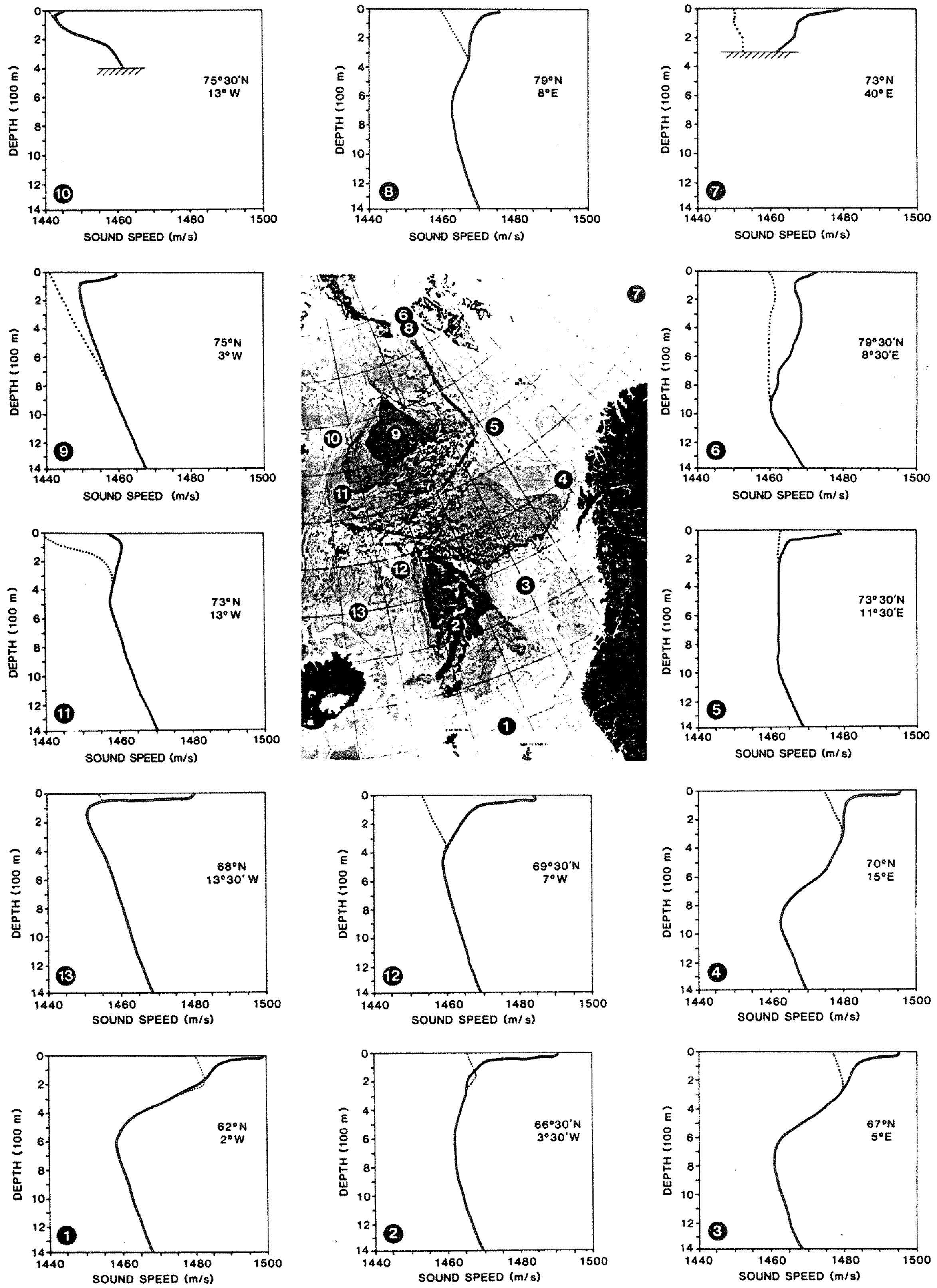


Fig. 4 — Representative sound-speed profiles in the Nordic Seas. The solid curves indicate summer, and the dotted curves indicate winter.

Fig. 7. Sound speed profiles from the Norwegian and Greenland seas, and the Fram Strait. The map in the middle shows the position of each profile. From Hurdle (1986).

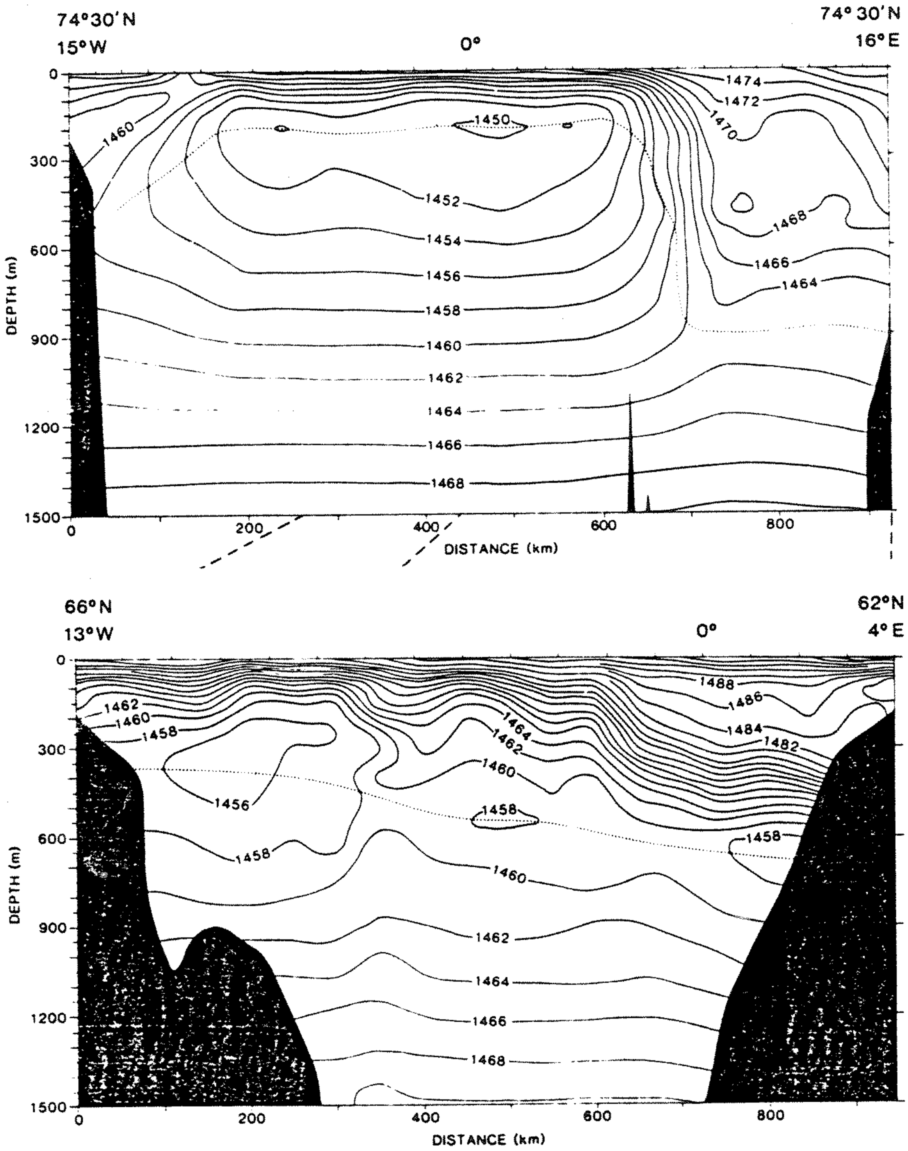


Fig. 8. Two W-E sections of sound speed during summer (August-September) in the Nordic Seas. The lower section is covering the southern parts, while the upper section is along 74 ° 30' N, across the Greenland Sea towards the Barents Sea. The dotted lines show the depth of the sound speed minimum. From Hurdle (1986).

2.3. Temporary hydrographic variations

The floats will most often be subject to hydrographic variations as they drift downstream entering different water masses. Changes in salinity or temperature will imply changed sound velocity, and may cause a change of depth of the float if there is no mechanism to compensate for the change in buoyancy.

The new float technologies take care of the latter effect, if required. Depth compensation may not always be wanted, as the measured depth change may give additional valuable scientific information.

Hydrographic changes in the waters between the sound source and the floats may cause fluctuations in signal travel time from the sound sources. This will make the positioning by acoustic triangulation noisy if special considerations are not taken during data analysis. In the Gulf Stream the passage of cyclonic (cold core) eddies or rings between the sound source and the receiver may cause large enhancement of sound transmission. The eddies will act as converging or diverging lenses, and interfere with the local SOFAR channel (Beckerle et al. 1980).

3. TECHNICAL DESCRIPTION OF THE RAFOS SYSTEM.

3.1. The Rafos Float

The RAFOS float is a small neutrally buoyant subsurface drifter (Rossby et al., 1986). The float consists of a glass pipe of about 1.5 m length and 0.1 m in diameter, which provides the flotation and housing of the electronics. In addition there is some attached ballast (about 1 kg) which is dropped at the end of the mission. The glass pipe is rounded in one end and is sealed with a aluminium plate at the other end. The pipe is made of standard borosilicate glass, and this pipe type is widely used in the industry.

The weight of the standard float is about 12 kg, but this may vary depending of the specific choice of the thickness of the glass and the length of the glass pipe. The main components are mounted on a PVC spar prior to insertion in the pipe. The battery pack is mounted at the bottom to make the float remain vertical after the float has dropped the ballast. Above the battery pack the acoustic receiver, the micro processor (CPU) and then the radio transmitter is mounted (Fig. 4).

At the top a copper foil antenna is glued on to the PVC spar. The antenna part of the float is above the sea surface after the subsurface mission has ended and the ballast has been dropped. The pressure gauge, acoustic hydrophone and the ballast are mounted at the aluminium endplate. A thermistor is mounted inside the float.

The ballast
The ballast weight is suspended under the float in a fishing line that is fastened to the float in a short piece of wire resistant to corrosion in seawater. After the end of the subsurface mission an electrical current is put on the wire (0.2 A in 2 min.) causing it to dissolve electrolytically. The weight then is released and the float ascends to the surface.

Microprocessor and programming
The microprocessors of the first generation of floats were programmed in assembly language, but now the most widely used floats are programmed in the high level language forth. The floats are also equipped with real time clocks that make it simple to set up listening schedules and length of the missions. After the floats have been sealed the communication with the float is done with an optical link through the glass and thus external connectors are not needed.

Launching Rafos floats
The size and weight of the RAFOS float makes the launch of the float an easy task compared to handling of the heavy SOFAR float that required use of a winch. The glass pipe is easily handled by a single person and if the freeboard of the ship allows for it, it may be eased into the water by hand. From larger vessels several different contraptions have been constructed to perform gentle launch of the floats.

The light weight has facilitated launch from ship of opportunity. The crew only pulls a magnet that turns on the self check the float goes through. At a given location the ship stops and drops the float in the water. In the Gulf Stream RAFOS floats were launched from a freighter that were trafficating a route from Norfolk, Virginia to Bermuda. The position for the launch was determined by the captain by dropping XBTs and then launching the float as the 15°C isotherm was at 400m depth. This resulted in launch close to the centre of the stream.

Isobaric and isopycnal floats
The glass housing of the RAFOS float has smaller compressibility than seawater. If the float is removed from the depth were it is neutrally buoyant it will give rise to pressure induced restoring forces. A float of this type is thus called an isobaric float. In order for a float to follow oceanic circulation with vertical motion it is necessary to make a float with the same compressibility as seawater. In order to achieve this a device that is more compressible than seawater is added to the float such that as a whole, the glass pipe and the added device, approximately have the same compressibility as seawater. A float with this device added is called an isopycnal float. No pressure induced restoring force will occur as the float experiences vertical excursions following the water motions. The device that is added is called a compressee. Since it is very difficult to match the compressibility completely, the float is most often made a little less compressible than sea water. This ensures that one does not induce overshooting.

3.2. Sound sources

The RAFOS float is equipped with a hydrophone which listens to acoustic signals transmitted by moored sound sources. The signal is an 80 s continuos wave pulse centred at 261 Hz. There is a linear frequency increase of 1.523 Hz over the 80 s duration of the signal. The hydrophone on the float that detects the signal is a small unit about 5cm long, while the sound sources are rather big and heavy units.

The size of the sound source is basically governed by the size of the resonator and the amount of batteries that is needed to put sound into the ocean. The standard sound source produced by Webb Res. Corp. (Fig. 9) is basically a moored SOFAR float that consists of two units, one unit housin the electronics and batteries and the other the sound projector. The projector is a free flooded "organ pipe" with the resonator sitting at one end of the ~1.7m long and 0.36m diameter pipe.

The battery and electronics housing is a 3 m long and 0.3 m diameter pipe. The total weight of the assembly is 360 kg in air and 140 kg submerged. The sound source is capable of 4,000 transmissions, and is thus made for multi year life. A typical transmission schedule may consist of 3 transmissions per day, resulting in about 4 years of life time for one deployment. In easily accessible areas the sound sources may be retrieved and refurbished for redeployment, but in remote areas this may not be cost effective.

The signal strength of the standard sound source is 183 dB re 1 micropascal at 1 m. This gives a useful detection range of about 2,000 km under ideal conditions with a well defined thermocline/sound-channel (Rossby et al., 1986). The actual operating range is mostly less than this, and in the Nordic Seas significantly less.

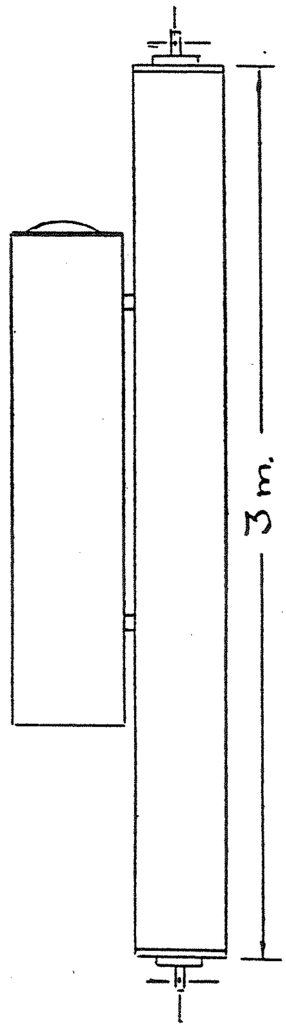
2/94

RAFOS MOORED SOUND SOURCE

Moored sound source, user programmable. Multi-year life, depending on application. Suitable for RAFOS and other applications.

Nominal Specifications:

Frequency range:	Standard RAFOS sweep, 261 Hz
SPL:	183 dB re 1 micropascal at 1 m
Projector:	"Organ-Pipe" free flooded, 36 cm diameter
Controller:	SeaScan/Tillier design. Programmable via external connector. Temperature compensated time base. (Delta f)/f = 5×10^{-8}
Batteries:	Alkaline "D" cell assembly
Endurance:	4000 transmissions
Maximum operating depth:	2000 m
Material:	Aluminum 6061-T6 End-caps hard anodized
Weight:	360 kg (140 kg submerged)
Mooring Tension Maximum:	4400 kg (10,000 kg with optional external tension member)



Note:
A HIGH-POWER version is being tested. Capable of 3000 transmissions at 189 dB re 1 micropascal at 1 m, or more transmissions at reduced power. Similar dimensions and weight.

Current Users:

Woods Hole Oceanographic Institution
University of Washington
University of Rhode Island
NOAA/Pacific Marine Environmental Laboratory
Institut fur Meereskunde, University of Kiel (Germany)
Institut Francais de Recherche pour L'Exloitation de la Mer (France)

Webb Research manufactures neutrally buoyant drifters, drifting profilers, RAFOS sound sources, and Tomography transceivers of a variety of standard and custom designs.

Fig. 9. Datasheet from Webb Research Corp., showing the moored sound source.

More powerful sound sources have been developed, and Webb Res. Corp. is testing a high power version of the source described above. It is based on the same principles but some modifications have been performed to increase the power output to 189 dB. The prototype is priced at 38,000 USD (1994).

A loud sound source has been developed by Sparton of Canada. This sound source is a resonant pipe projector and consist of a free-flooded pipe with a ceramic-steel driver ring at its midsection. The source level is 195.5 dB re 1 micropascal at 1 m, and it has an energy efficiency of 85% at resonance (260Hz). The cost of the resonator itself is 50-60,000 USD, and of the electronics 15-20,000 USD. Four units of the Sparton design have performed excellent during a RAFOS experiment in the North West Atlantic (Rossby pers. com.).

3.3. Ballasting

Ballasting a float means to accurately adjust its mass. The goal of ballasting the floats is to make them neutrally buoyant at a desired pressure (depth) for an isobaric float or at a desired density surface for an isopycnal float.

The ballasting is carried out at elevated pressure and there are several reasons for doing this. One reason is that even though the glass pipe is less compressible than seawater, the compression is significant and has to be considered. Neglecting the compressibility altogether would yield an error of 32 g at 1000 dbar (for an isobaric float), and this again would give a depth error of about 800 m for a float targeted at 1000 m in the North Pacific (Swift and Riser 1994).

The compressee which the isopycnal floats are equipped with do not respond linearly to pressure changes at low pressures and due to this it is necessary to pressurize them to a pressure comparable to the desired operating pressure (Rossby et al., 1986). This is not necessary for isobaric floats,but the ballasting still has to cover a pressure range such that extrapolation to higher pressure does not introduce too large errors. E.g. Swift and Riser (1984) used ballasting data for the pressure range from 200-700 dbar for "isobaric" floats targeted at 1000 dbar. However if the isobaric floats are pressurized to intended working pressure the volume at that pressure is exactly known and it is only necessary to make a small temperature correction (accurate knowledge of compressibility is not needed) (Rossby 1994, in Bower 1994).

The uncertainty in ballasting is about 1g for the most accurate procedures, giving an uncertainty of neutral buoyancy depth of about 25 m (depends on stratification) for isobaric floats. The elevated pressure also eliminates the problem with air bubbles that may adhere to the float as it is immersed in water at atmospheric pressure and thus introduce errors. The pressurizing also works as a check for leaks in the float.

Since the ballasting is carried out at elevated pressure, a facility with a pressure vessel (tank) is needed. Fig. 10 shows a schematic view of the tank that is used at University of Rhode Island. The floats are placed in a vertical position in a pressure vessel, and the vessel has to be about 2 m high and a have an inner diameter somewhat larger than the floats (e.g. 30 cm is sufficient for a pair of floats).

A light flexible chain is hung underneath the isobaric float. As pressure is applied an isobaric float gains buoyancy because it is less compressible than the surrounding water. So when the float rises as pressure increases it lifts more chain from the bottom of the pressure vessel untill it is neutrally buoyant. The magnitude of the vertical excursion and the weight of lifted chain are proportional to the increase in buoyancy at the elevated pressure. One way of measuring this vertical excursion is by reading a scale placed inside the float through a window in the tank (Fig. 10).

Water quality:
The temperature and the conductivity of the tank water must be measured during ballasting in order to be able to compute the water density. Experience has shown that the mineral content in tap water introduce an uncertainty in the density of the water. It has therefore been recommended to use deionized water, or to measure the density of the tank water directly.

The float group at University of Rhode Island has developed a computer program (in Matlab) that calculates the mass that has to be added to the float, based on data from the ballasting and environmental parameters (T, S and p) at the target depth. The ballasting data are entered into the program during the ballasting, and thus the program provides a quality control of the ballasting procedure too.

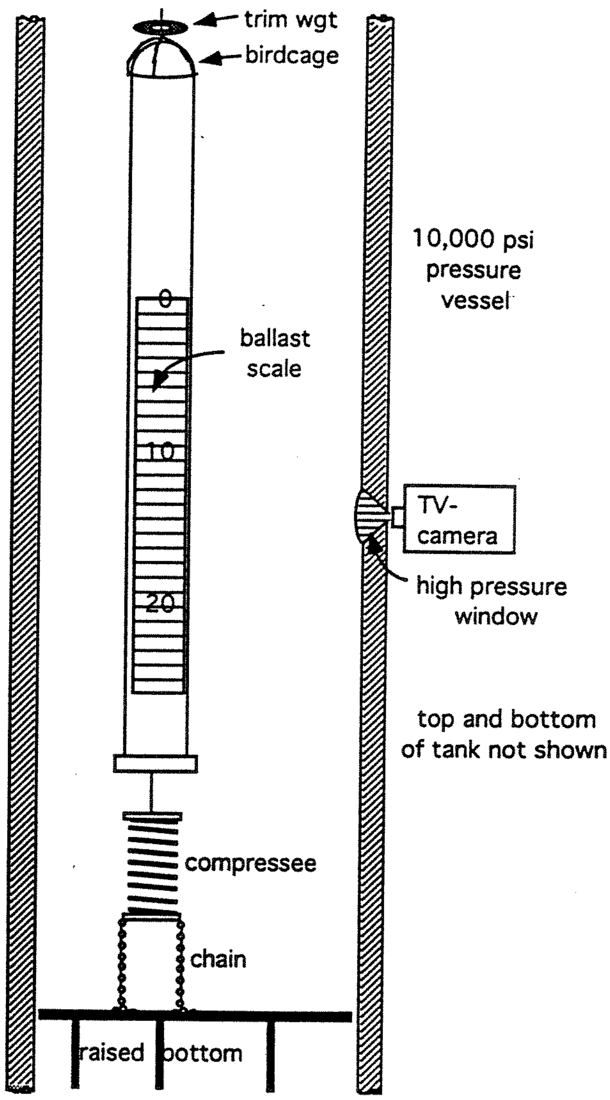


Fig. 10. Schematic view of one of the the ballasting tanks at the University of Rhode Island. The inner diameter for this tank is about 35 cm, and the height about 3.6 m. A wider, but shorter tank is also available.

3.4. Data transmission

The data representing the positions (sound pulse travel times) of the float during its mission are continuously stored in the internal memory of the RAFOS float. When the mission is ended and the float surfaces, the Argos PTT transmitter is activated, sending the position data in 256-bit messages to one of the earth orbiting Argos satellites.

The float transmits messages at a given interval (~43s), and the float picks the messages from memory such that if the float fails before all messages are received there is a fair chance that data from all parts of the mission is received.

The messages are transmitted according to the ARGOS data format specifications. Each message sent by the float contains 32 bytes of data, but only a fraction of the messages are actually picked up by the ARGOS satellites. Typically 60-80% of the messages are received the first day, and it takes several days before the data transfer is complete (batteries last about 14 days). This is dependent on the weather condition (heavy sea states increase the time) and also on the geographic position. Since the ARGOS satellites are polar orbiting there is a greater chance of having a satellite above the horizon at high latitudes, which experiments in the Nordic Sea may benefit from.

After the data have been collected by the ARGOS satellite and processed at a ground station the data are mailed via Internet a couple of hours after the message was received by the satellite. The data consists of the time of arrival of the acoustic signals, pressure and temperature. In addition ARGOS provides the surface position of the float and accurate time of data transmission. The timing information received from ARGOS is very important and is used to correct the float clock which may drift several seconds during a long mission.

Preferably the float should be in the vertical with sufficient freeboard for its Argos antenna to stay out of the water. The required "natural" freeboard (about 35 cm for the Seascan standard float) after surfacing has to be considered when preparing the floats with batteries etc.

The Argos system

The Argos system have been in operation for more than 15 years. It consists presently (1994) of two Tiros-N series NOAA polar-orbiting satellites, providing worldwide coverage, and two processing centres (GPCs), in Toulouse, France and Landover, MD, USA. In addition, several ground receiving stations secure real-time or near real-time reception over large areas (Fig. 11).

Today the system serves users in about 45 countries, with about 4,500 transmitters (PTTs) in operation (Ortega 1994). More than 50% of the transmitters are mounted on regular surface drifting buoys used for e.g. meteorological purposes.

There is about 10 satellite passes per day at mid-latitudes, and 28 in polar regions.

3.5. Post processing of acoustic data

The first task after receiving the data from the Systeme Argos is to sort the data according to platform ID number. The next step is to unscramble the raw data, check for redundancy and sort out bad data messages. To the unscrambled data, calibration coefficients are applied and time of arrival of sound signals in seconds, temperature in °C and pressure in decibar are calculated.

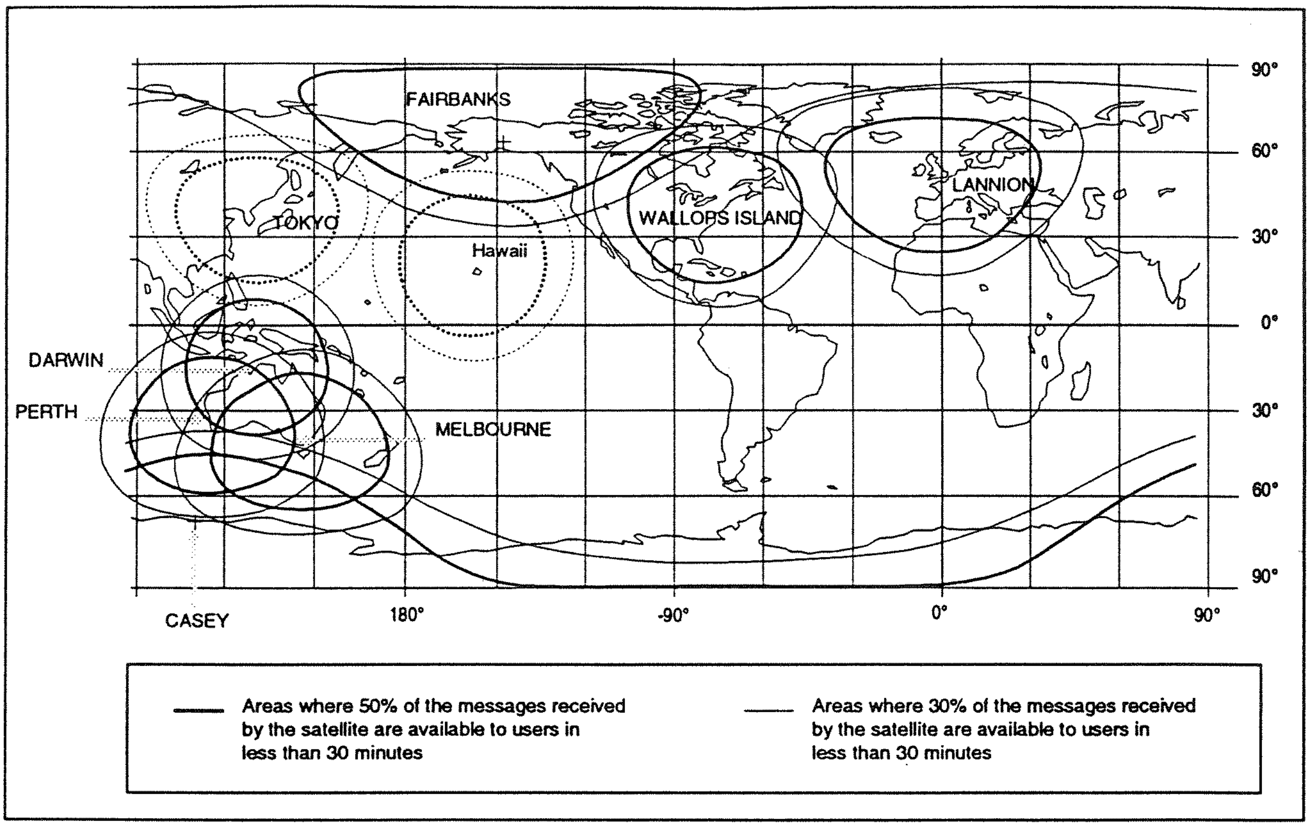


Fig. 11. Areas served by Argos real-time coverage (from Ortega, 1994)

With the data processing programs available, the processing of the temperature and pressure measurements are straightforward. The tracking of the floats is a more time consuming affair. To compute the position of the float the following information is needed:

- positions of sound sources,
- the time of signal transmission,
- the time of arrival of signal at the float and
- the average speed of sound.

The time of signal arrival is given relative to the float clock. Before the travel times are computed the float clock must be corrected for offset at launch and reception times by Systeme Argos at the end of the mission.

Most of the effort in the tracking procedure is in editing the travel time data. Manual editing is used to sort out erroneous data points by visual inspection, and if the float has listened to more than one sound source in one "window" the signals have to be split. Depending on the quality of time-of-arrival data, the time required for this task varies a lot.

If the acoustic reception has been marginal, it is quite a job to edit the travel time data. On the other hand with one "clean" signal the editing is quickly accomplished. The launch position is used as a first guess in calculating the first position and each position is used as a first guess in the iterative position calculation of the next position.

3.6. The volume changer ("VOCHA")

Changes in stratification along a trajectory are caused by physical prosesses such as divergence in the velocity field or winter convection and mixing. In order to measure the stratification with RAFOS floats, a device (VOCHA) has been added that enables the float to change the volume by a small amount. An increase/decrease in the volume cause the volume to raise/sink to a different density surface. Since the volume change is well defined the densities at the two levels at each side of the equilibrium density are known.

By measuring the pressures (depths) the vertical distance is known and the stratificaction over a definite interval is determined. The volume of the float is changed by a moving piston in a pipe that is in connection with the ambient water. The piston is pushed by a small screwdriver motor connected to a translational threaded shaft. This simple VOCHA is able to change the volume of the float by a couple of cubic centimeters, which is enough to make a measurement of the stratification. The vertical distance the float moves is dependent on the density stratification, and is a measure of the stretching vorticity changes along the path of the float (Rossby at al. 1993).

In the North Atlantic Current experiment the floats are equipped with the VOCHA. Data from one of these floats are shown in figure 12. The different colors depict the different levels the float reached. The float remains at the intermediate pressure most of the time, but by a small increase in volume it rises to a lower pressure (shallower), and then the the float volume is decreased and the float moves to a higher pressure. A last it moves back to the " middle pressure". This trip to both sides of the mid pressure that may be performed several times per day gives a measure of the stratification.

The sharp drop in pressure, from ~500 to 1000 db around day 150, shows that the float moved from one side of the stream to the other. From the pressure difference it can be seen that the straification is different at the two sides of the stream. The trajectory shows that the float was in an eddy on the western side of the stream and moved quickly across the stream and was then entangeled into eddy motion again.

3.7. Recovery of Floats

Floats are seldom recovered. When the float stops transmitting its data due to battery exhaustion, its mission generally is ended. Still it is possible from the Argos positioning to locate and recover the floats, but the cost may be prohibitive. During the AMUSE program in 1993-94 to study the fate of the Mediterranean water in the NE Atlantic, nine isobaric floats were recovered, using Argos satellite fixes and an ARGOS RDF (Radio Directional Finder). Recoverable floats have also been used in intensive studies of Gulf Stream meanders.

3.8. Experiments with RAFOS floats

Since the RAFOS Float Pilot studies in the Gulf Stream in 1984-85 RAFOS floats have been, and are used in a number of experiments in both the Atlantic and the Pacific Oceans. Some of the major experiments are mentioned below.

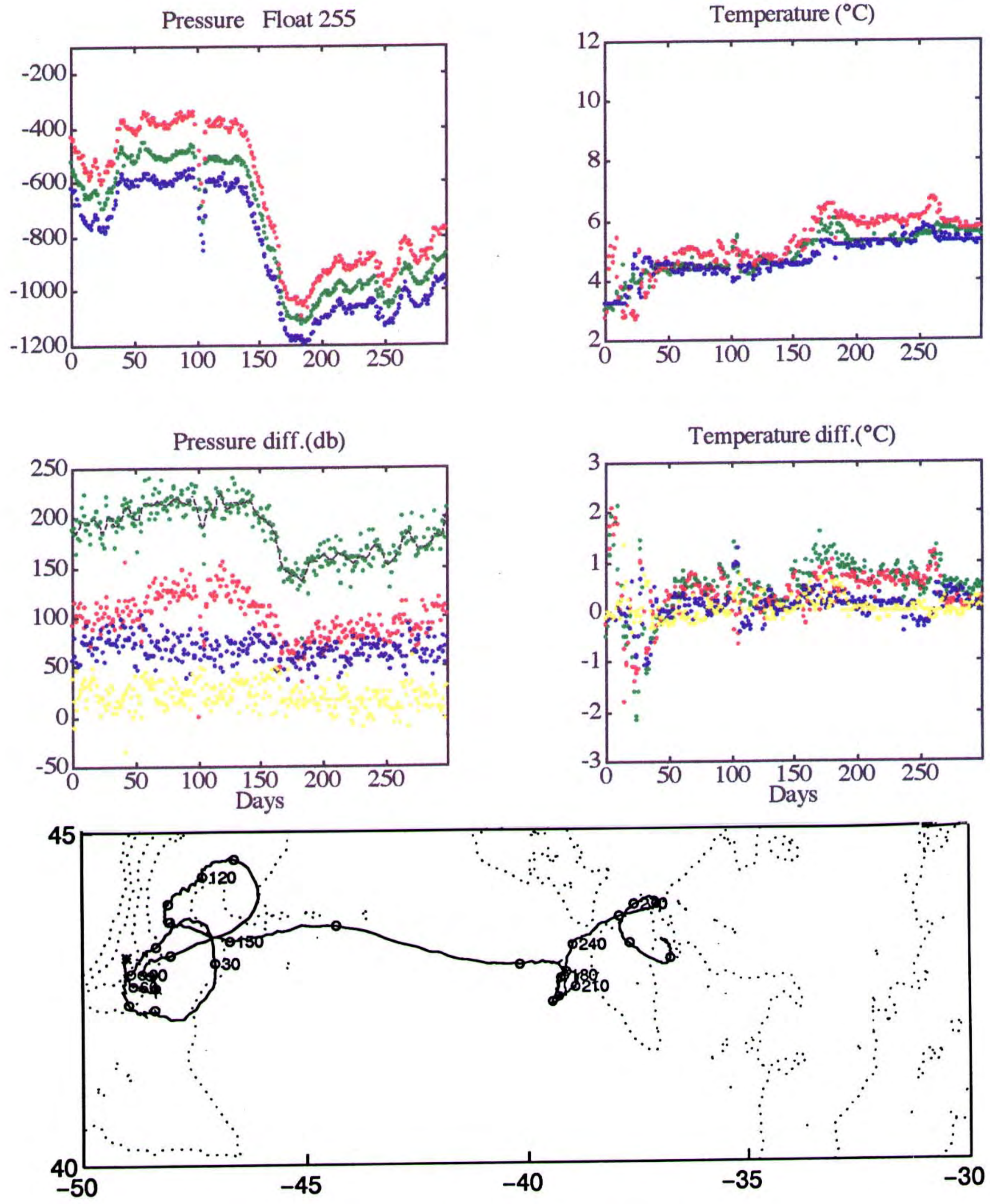


Fig. 12. The two upper panels show the measured pressure and temperature of a rafos float equipped with the VOCHA as the float fluctuates up and down from its reference pressure (green curve). The next two panels show the calculated pressure and temperature differences between the levels, while the yellow dots show the differences in pressure (temperature) at the begining and end of each excursion. The trajectory of this float is shown below. These figures were kindly provided by prof. Tom Rossby.

The RAFOS pilot studies were followed up by the float component of the *Synoptic Ocean Prediction Experiment* in which about 75 floats were launched in the Gulf Stream from 1988 to 1990. With a total of about 100 float tracks, these float experiments have given new insight into the kinematics and dynamics of the Gulf Stream. Both projects were carried out by Tom Rossby and his group at the University of Rhode Island. This group is now involved in an experiment in the North Atlantic Current (Newfoundland Basin area) to study the circulation and modification of water masses by winter convection. The about 100 floats used in this experiment are RAFOS floats with a volume changer ("Vocha", see below) device added to standard isopycnal RAFOS floats.

In the Eastern Atlantic RAFOS floats have successfully been used to document the formation of meddies (Mediterranian eddies). Meddies are formed south west of Portugal, in the subsurface flow of water originating in the Mediterranean (the Medtierranean Undercurrent). The *Mediterranean Undercurrent Seeding Experiment* is run by scientists at Woods Hole Oceanographic Institution (WHOI) in collaboration with Portugese scientists. About 40 floats have been deployed in this program, and in the same area scientists from Kiel have deployed 50 floats to study the circulation in the Iberian basin. In a study of the circulation in the deep South West Atlantic (5N-35S), a large RAFOS float program is run by scientists at WHOI. In this experiment, which is a part of the WOCE, a total of about 200 RAFOS floats will be deployed in this area were the circulation is pooly charted.

In the Western North Pacific more than 90 RAFOS floats have been used in studies of mid depth (~1000 m) circulation in this region. These floats have been deployed under three different programs, one is a part of WOCE, but they are all run by scientists at the University of Washington in Seattle. Scientists at The Naval Post Graduate School in Monterey, USA, use RAFOS floats to study the California Undercurrent.

4. SOME SUGGESTED EXPERIMENTS IN NORDIC WATERS

The subsurface drifter technology has been rapidly developing the past 10-20 years. Off-the-shelf equipment may now be applied routineously as an oceanographic tool by users not necessarily having detailed technical knowledge as such. In this case Nordic oceanographers with their wide ranging experience and their logistics resources (ships etc.) should fairly easily adapt to this new technology.

In future scientific programmes involving subsurface drifters most resources may be spent directly on managing and performing the basic science, and less on solving technological problems and developing new instruments. The demand for qualified personnel both to design the experiment and to handle the data should not be underestimated. When designing an experiment, the time requirements for data retrieval and postprocessing as well as further analysis must be kept in mind. Training of personnel must be performed, preferably in cooperation with insitutions already familiar with this kind of data.

4.1. Regional studies

Presently the most exciting property of subsurface drifters is their ability to track and resolve even very slow currents in deep and bottom waters. Mapping of meso- and large scale circulation have so far been the typical purpose for experiments elsewhere. For the Nordic scientific community experiments in the Nordic Seas (Norwegian, Greenland and Iceland Seas) will be most relevant. But with new technologies underway involving e.g. reuseable drifters also small-scale experiments in enclosed waters bodies such as fjords may be performed.

4.1.1. The Nordic Seas

The Nordic Seas are important links between the cold Arctic and the warm subtropical waters. The Nordic Seas have long been recognized for their important role in the transformation of surface or near surface water masses and the formation of deep and bottom water that supply deep water both into the Arctic Ocean (Polar Basin) and the North Atlantic. See e.g. Hopkins, 1988. In this context carefully designed experiments with subsurface drifters in this region are practically guaranteed to give new and important insight into both internal and exchange processes.

New measurements of the deep water circulation between the Greenland and Norwegian Seas indicate that the flow direction which until recently was considered to to be practically unidirectional into the Norwegian Sea (Sælen, 1990) has reversed (Østerhus and Gammelsrød, 1995). This reversal is accompanied by an observed rapid warming of the Norwegian Sea deep water (Østerhus and Gammelsrød, 1995), and may be coupled to regional or even global changes in the climate.

Thee are many unresolved questions related to the water exchange between the Nordic Seas and the Arctic Ocean through Fram Strait, both for the Atlantic Water (Manley, 1995) and for the deep water.

Also the water exchange between the Norwegian and the Barents Seas, and the fate of dense bottom water from the Barents Sea that spreads at depth in the Norwegian Sea is practically unknown (Blindheim 1987).

The internal flow pattern within the deep Norwegian and Lofoten Basins needs to be better mapped, in order to make it possible to understand and quantify residence times and exchange processes. Without any direct evidence from measurements it has been speculated that some kind of circular motions along the peripheries exist (Mauritzen, 1993).

Deep water fishing in the Nordic Seas and in other oceans is rapidly developing as new and more robust fishing gear come available. New commercially exploitable stocks and species are discovered each year. But the migration and recruitment of these deep water species are generally very little known. It may be more than an educated guess to claim that the deep currents including their variability play an important role for these biological processes. An increased knowledge in this field will enable much better recommendations for fishing quotas to be made.

The first oil production wells may soon be established on the Vøring Plateau at depths larger than 1,000 m, and exploration will increase in the Norwegian Sea (NOD 1995). As for oil exploration elsewhere, it is important to have a basic knowledge of the circulation, both for contingency planning and for engineering purposes, and measurements will have to be performed according to the requirements and responsibilities of the licenced companies. At such large depths the commonly used oil disperison models may be inadequate, as a big portion of the oil in the case of a leak at the bottom may be dispersed and circulated within the water column in stead of at the surface. Also the fate of other potential pollutants at such large depths and pressures may be different from what is experienced at shallower depths in the North Sea and elsewhere.

The dispersion of various forms of pollutants in the deep water of the Nordic Seas has been subject to investigations. Tracer measurements show that radioactivity from e.g. UK and France is widely spread northwards. However, with the sparse station material available, only very coarse flow paths may be described. Also dispersion paths from single sources such as leaking reactors of sunken nuclear powered vessels are hard to determine with single point measurements, although attempts have been made in connection with a sunken Russian submarine (Sætre, 1994).

The Nordic Seas serve both as habitat and migration route for fish species such as herring, which at times along with zooplankton descend very deep. The coupling between the circulation pattern in the upper deep water and the growth and migration of these and other species are little known (Skjoldal, 1993). The use of subsurface drifters to resolve the flow pattern should provide valuable insight into many unresolved biological questions for the region.

The scientific issues mentioned above are some of several more that may be effectively explored by means of subsurface drifters such as RAFOS floats. We have not mentioned that also the drifter technology may be a valuable tool for establishing and also validating numerical models for deep water circulation. It should also be mentioned that deploying subsurface fixed current meter moorings on the shelf slopes may inflict with commercial fishing activities even for depths larger than 1,000 m, with the risk of damaging both gear and instruments. This risk will be eliminated when using subsurface drifters.

The Greenland Sea

The Greenland Sea is a region of exceptional vertical homogeneity, where deep convection is taking place during winter. The convection makes this region a very interesting study area in oceanography and climatological studies. The weak vertical density gradients especially in the Greenland Gyre proper, makes the calibration of isopycnal floats more difficult than elsewhere. Thus isobaric floats seem to be the better option for this region.

The sound speed minimum at the surface causes the rays to concentrate near the surface (Fig. 13). This will reduce the range of the sound signals, but significant results may still be achieved. *The Greenland Sea Tomography Experiment* (supported by NSF and ONR in the USA) was successfully conducted in 1988-89. Arrays of 250 Hz sound sources and receivers were mounted between 95 and 190 m depth (Sutton et al. 1994).

4.1.2. The Polar Basin

As mentioned in previous chapters, the use of subsurface drifters under the Arctic ice has been of limited success. Different proposals have been launched, which have stranded either due to lack of funding or coordination, or both.

The sound propagation characteristics limit the signal distance under the ice. Still it will be possible to suspend sound sources or alternatively listening hydrophones from small radio or satellite transmitters on the drifting ice, then being able to track subsurface drifters over long distances. Questions on residence times and on the fate of the Atlantic Water in the Arctic Ocean are constantly being raised, with presently inadequate data.

The funding requirement for a large-scale experiment in the Arctic Ocean as well as elsewhere will amount to several million Norwegian kroner (NOK) in basic equipment cost only. Therefore the possibility to launch joint projects involving several institutions outside the Nordic community is recommended and should be seriously evaluated. An inter-Nordic experiment with the cooperation with one experienced institution from e.g. USA is a relevant option.

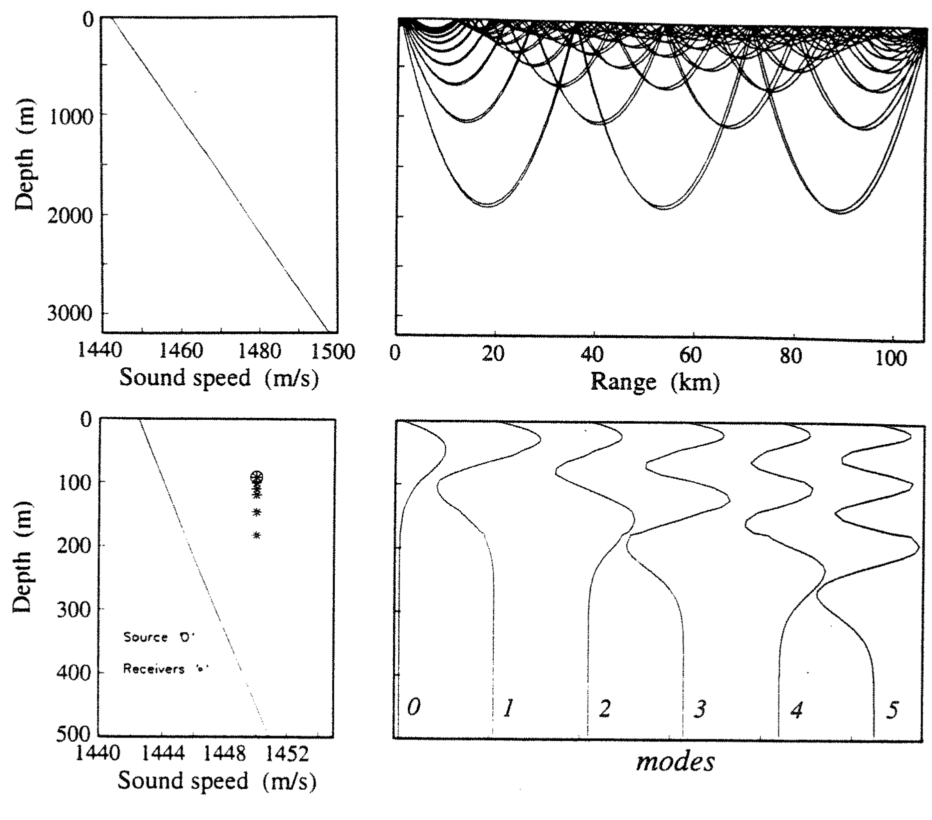


Fig. 13. Calculated sound ray paths and vertical modes in the Greenland Sea from a linear sound speed profile (left). From Sutton et al. 1994.

4.1.3. The Baltic and Fjords

The Baltic has many unresolved questions related to the limited water exchange and the heavy load of various pollutants (Monitor, 1988). The deep basins suffer from anoxia, and fish and other species have shown elevated concentrations of organic pollutants in their tissue.

Experiments with subsurface drifters in such an enclosed water body may give new insight into questions related to the water circulation and to the origin and fate of pollutants. Such experiments will have a much smaller scale than for the open ocean, and the traditional acoustic positioning may be inadequate. In stead, the drifter types that ascend/descend automatically at preset time intervals (e.g. ALACE, MARVOR) for Argos or GPS positioning may be the best solution. Experiments with subsurface drifters in the Baltic should call for concerted actions from several nations, including the Nordic.

Fjords, which are mostly found in Norway, may have complex deep water circulation, partly due to the intermittency of water renewal (only occasional sill overflows) and partly due to complicated topograpy. Crucial questions from an environmental management point of view may be connected with the renewal rate of the deep water, the carrying capacity for nutrient and organic load and with the the fate of subsurface pollutant discharges. Measurements at one or a few fixed positions are often inadequate to resolve these questions.

As for the Baltic, use of subsurface drifters in these enclosed water bodies will also have to adapt to alternative measurement strategies, but should then become valuable tools for answering the questions. Positioning from ships by means of high frequency (kHz) sound will be possible. Light-weight SOFAR type floats (that transmit sound) could be used.

4.2. Additonal sensors

The first floats had no sensors to measure environmental parameters. As temperature compensating SOFAR floats came into use both temperature and pressure were measured and telemetered from the SOFAR floats (after 1975). Later conductivity sensors have been incorporated.

New sensors for oceanographic measurements are continuously being developed. Some of these are also being adapted to the subsurface drifters. But technical performance limitations (lifetime, accuracy, power consumption) of the sensors may so far have limited their use for float applications.

It may also be that the traditional user communities of sensors measuring chemical or biological parameters are only marginally aware of the subsurface drifter technology and its possibilities.

Combined studies with traditional surface or near surface drifters and biological sampling have successfully been performed (see e.g. Lobel and Robinson 1988). Automatic and unattended sampling of biological and other properties of the ocean are relatively new, and have generally been done from moored buoys. During the past 5-10 years also near surface drifters have been equipped with sensors such as fluorometer, spectroradiometer and transmissiometer as well as automated water sampler (Abbot et al. 1990).

Experiments with fluorometers on RAFOS and ALACE type floats have already been performed, and the range of parameters to be measured automaticaly is steadily increasing. Thus the possbility to mount new sensors to the existing platforms should be considered also when launching the first experiment with acoustically positioned subsurface drifters such as RAFOS floats by Nordic communities.

4.3. Environmental concern

The Use of high energy sound sources has raised some questions among environmentalists that the sound pulses may be harmful to marine wildlife, like whales (Shurkin 1994). Thus some remarks on this issue with relation to the present study may be made.

Many marine mammals use sound for communication and navigation. Dolphins uses the echoes from the high-frequency sounds they produce in order to navigate, and they use moderate-frequency sounds to communicate among individuals. It may be expected that ambient noise even from natural sources which spans a wide variety of frequencies and intensities (Fig. 14) will disturb or interrupt communication and navigation.

The U.S. National Research Council (NRC) in 1992 established a multi-disciplinary committee with main charges to review the current state of knowledge and ongoing research on the effects of low-frequency (1-1,000 Hz) sound on marine mammals. The main findings (Merrell 1994) were that data to assess impacts were very scarce. For those few mammals where data exist, it seems that even high-level low-frequency sound is barely audible to them.

Some evidence suggests that members of the baleen whales (gray, fin, humpback whales) are much more sensible than are members of the toothed whale suborder. Baleen whales are known to produce low-frequency sounds that propagate over long distances. The upcoming ATOC (Acoustic Thermometry Ocean Climate) programme is preparing to use 60/90 Hz, 195 decibel soundsources for long distance sound transmission (California-Hawaii).

The purpose of ATOC is to detect changes in travel time due to changing ocean temperatures. As there has been very little research on sound effects on marine mammals, a marine mammologist research programme will be conducted jointly with the ATOC pilot programme (White 1994).

Similar discussions may be raised when acoustic techniques will be applied in Nordic waters. Some experience may be hauled from previous research on effects from seismic sound waves related to offshore oil field surveys. Although probably of little practical concern, the environmental issue still will have to be considered in future drifter experiments.

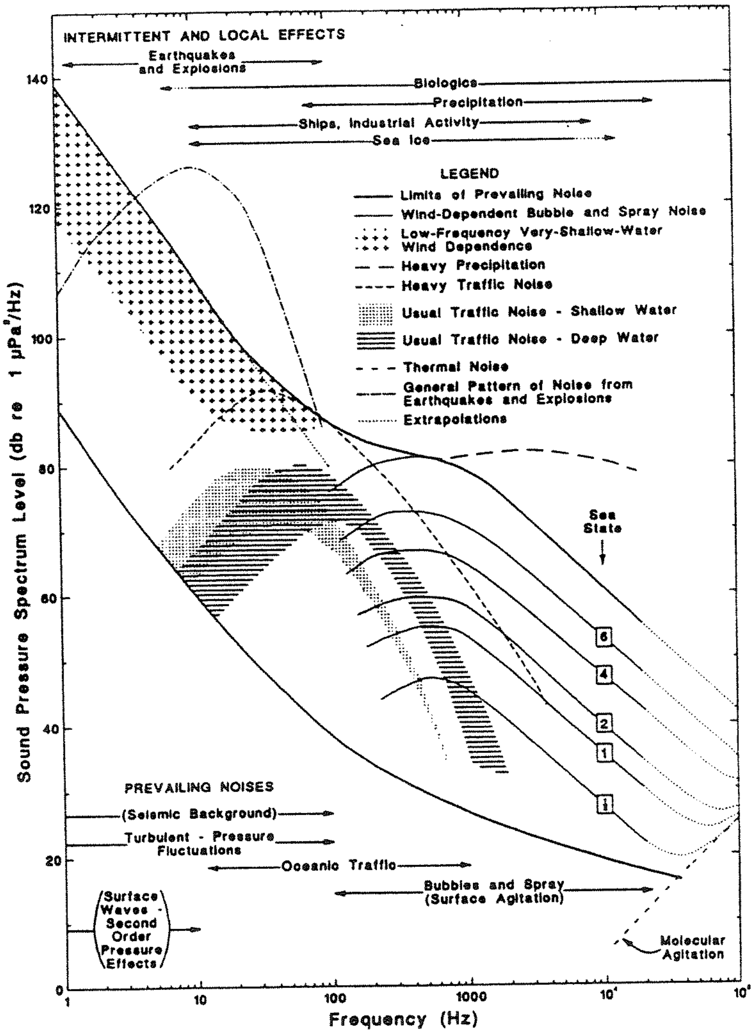


Fig. 14. Distribution of ambient noise spectra from different sources (time-averaged values), adapted from Wenz (1962). The left axis uses the water standard for decibel calculation.

5. LITERATURE

Abbot, M. R., K. H. Brink, C. R. Booth, D. Balsco, L. A. Codispoti, P. P. Niiler and S. H. Ramp 1990: Observations of phytoplankton and nutrients from a Lagrangian drifter off northern California. Journ. of Geophys. Res., Vol. 95, No C6, pp. 9393-9409.

Anderson-Fontana, S. and T. Rossby 1991: RAFOS floats in the SYNOP Experiment 1988-1990. Techn. Rep. 91-7, Univ. of Rhode Island, USA.

Beckerle, J.C., L. Baxter, R.P. Porter and R.C. Spindel 1980: Sound channel propagation through eddies southeast of the Gulf Stream. J. Acoust. Soc. Am. Vol. 68, No. 6, pp. 1750-1767.

Blindheim, J. 1987: Cascading of Barents Sea Bottom Water into the Norwegian Sea. ICES Paper No. 61/87, Copenhagen, 8 p.

Bower, A. S. 1994: RAFOS Float Technology Workshop, WHOI Jan. 13-14 1994. Proceedings, WHOI, Mass, 115 p.

Cheney, R. E., W. H. Gemmill, M.K. Shank, PIL. Rickardson and D. Webb 1976: Tracking a Gulf Stream Ring with SOFAR Floats. Journ. Phys. Ocean. Vol. 6, pp-741-749.

Colony, R. 1986: Initiating an Arctic Sofar Program. Proceedings, MDS '86, pp. 81-85.

Davies, R. E., J.E. Doufour, G.J. Parks and M.R. Perkins 1982: Two inexpensive current-following drifters. SIO Reference 82-28, Scripps inst. of Oceanography, San Diego.

Davis, R. E., D.C. Webb, L.A. Regier and J. Dufour, 1992: The Autonomous Lagrangian Circulation Explorer (ALACE). Journal of Atmospheric and Oceanic Technology, Vol. 9, No. 3, 264-285.

Hopkins, T. S. 1988: The GIN Sea. Review of physical oceanography and literature from 1972. Rep. SR-124, SACLANT Centre, San Bartolomeo, Italy, 190 p.

Hurdle, B. G. 1986: The Sound Speed Structure. In: The Nordic Seas, B. G. Hurdle, Editor, Springer-Verlag, 778 p.

Knutz, T., J. Cohrs and A. Talmat 1995: 'Kiel-Tiefenfinder' - Free tracking subsurface float. Sea Technology, Febr. 1995, pp. 55-60.

König, H and W. Zenk 1992: Principles of Rafos technology at the institut für Meereskunde, Kiel. Ber. Inst. Meeresk., Kiel.

Lobel, P. S. and. A. R. Robinson 1988: Larval fishes and zooplankton in a cyclonic eddy in Hawaiian waters. Journ. of plankton res. Vol. 10, No. 6, pp. 1209-1223.

Manley, T. O., J-C. Gascard and W. Brechner Owens 1989: The polar floats program. IEEE journ. of ocean. engineering Vol. 14, No. 2, pp. 186-194.

Manley, T. O. 1995: Branching of Atlantic Water within the Greenland-Spitsbergen Passage: An estimate of recirculation. Journ. Gephys. Res. Vol. 100, No. C10, pp. 20,627-20,634.

Mauritzen, C. 1993: A study of the large scale circulation and water mass transformation in the Nordic Seas and Arctic Ocean. Ph.D. thesis, MIT/WHOI, WHOI rep. No. 93-53, 212 p.

McKeown, D.L. 1989: A near surface drifter acoustic tracking system. Oceans '89, Seattle, Wa, proceedings, Vol. 3, pp. 875-879.

Merrell, W. 1994: Low-Frequency Sound and Marine Mammals. Current Knowledge and Research Needs. National Academy Press, Washington D.C., 75 p.

Monitor 1988: Östersjön ock Västerhavet-livsmiljöer i förändring. Naturvårdsverket, Sweden, 207 p.

NOD 1995: Facts about the Norwegian Petroleum Activities, 1995. The Norw. dept. of Industry and Energy, Oslo, 130 p.

Neuman, G. and W. J. Pierson 1966: Principles of Physical Oceanography. Prentice Hall Inc., N.J., 545 p.

Ollitraut, M., G. Loaec and C. Dumortier 1994: MARVOR: A Multi-Cycle Rafos-float. Sea Technology Feb 1994, pp 39-44.

Ortega, C. 1994: Global Ocean Observation with Argos. Rep. CLS, Toulouse, 25 p.

Owens, B. 1991: A statistical description of the mean circulation and eddy variabiliy in the northwestern Atlantic using SOFAR floats. Prog. Oceanog. Vol. 28, pp. 257-303.

Pickard, G. L. and W. J. Emery 1986: Descriptive Physical Oceanography. An Introduction. 4th edition, Pergamon Press, 249 p.

Resio, D. T. and E. B. Hands (1994): Understanding and interpreting Seabed Drifter (SBD) Data. US Army Corps of Engineers, Washington DC, Techn. Rep. No. DRP-94-1, 152 p.

Rossby, H.T., A. D. Voorhis and D. Webb 1975: A quasi-Lagrangian study of mid-ocean variability using long-range SOFAR floats. Journ. of Marine Res., Vol. 33, pp. 355-382.

Rossby, T, D. Dorson and J. Fontaine, 1986: The RAFOS System. Journal of Atmospheric and Oceanic Technology, Vol 3, No. 4, 672-679.

Rossby, H.T., J. Price and D. Webb 1986: The spartial and temporal evolution of a cluster of SOFAR floats in the POLYMODE Local Dynamics Experiment. Journ. Phys. Ocean., Vol. 16, No. 3, pp. 428-442.

Rossby, H. T. 1987: Recent studies of fluid motion in the Gulf stream. Maritimes Vol. 31, No. 3, pp. 1-4.

Rossby, T., J. Fontaine and E. C. Carter, 1993: The f/h float - measuring stretching vorticity directly. Deep Sea Res., Vol. 41, No. 7, pp. 975-992.

Rossby, T., 1994: Remarks on RAFOS float ballasting at URI. In: Bower (1994).

Sælen, 1990: On the exchange of bottom water between the Greenland and Norwegian Seas. In: Nordic Perspectives in Oceanography. Acta Geophysica, 3, Göteborg, pp. 133-144.

Sætre, R (ed.). 1994: The sunken nuclear submarine in the Norwegian Sea. A potential environmental problem? Rep. Fisken og Havet, No. 7/94, Inst. Mar. Res., Bergen, 46 p.

Shurkin, J. 1994: Ocean experiment is put on hold. NATURE, Vol. 368, No 6472, p 573.

Skjoldal, H. R., T. T. Noji, J. Giske, J. H. Fosså, J. Blindheim and S. Sundby 1993: MARE COGNITUM. Science Plan. Rep. Inst. Mar. Res., Bergen, 162 p.

Stommel, H. 1955: Direct measurements of sub-surface currents. Deep Sea Res., Vol. 2, pp. 284-285.

Sutton, P., W.M.L. Morawitz, B.D. Cornuelle, G. Masters and P.F. Worcester 1994: Incorporation of acoustic normal mode data into tomographic inversions in the Greenland Sea. Journ. Gephys. Res. Vol.

Swallow, J. C. 1955: A neutral-buoyancy float for measuring deep current. Deep Sea Res., Vol. 3, pp. 74-81.

Swift, D. D: and S. Riser, 1994: RAFOS Floats: Defining and Targeting Surfaces of Neutral Buoyancy. Journal of Atmospheric and Oceanic Technology, Vol. 11, 1079-1092.

Voorhis, A. D. and D. C. Webb 1970: Large vertical currents observed in a winter sinking region of the NW Mediterranean. Cahiers Oceanographiques, Vol 22, No 6, pp. 571-580.

Webb, D. C. and L. V. Worthington 1968: Measurements of vertical water movement in the Cayman Basin. Deep Sea Res., Vol. 15, pp. 609-612.

Wenz, G.M. 1962: Acoustic ambient noise in the ocean: Spectra and sources. J. Acoust. Soc. Am. 34(12), pp 1936-1956.

White, M. C. 1994: Underwater sound tests meet controversy. EOS (Transactions Am. Gephys. Union), Vol 75, No 15 pp. 177-178.

Wilson, T. C. 1992: A small low-cost autonomous high-resolution drifter with telemetry through Argos and vhf packet radio. MTS '92, Washington DC, global ocean partnership, proceedings, pp. 486-492.

Østerhus, S. and T. Gammelsrød 1995: The Abyss of the Nordic Seas is warming. Paper 5 Nov. 1995, in prep. for subm.

APPENDIX 1, the UNESCO equation for sound speed in the ocean, as a function of salinity, temperature and pressure.

```
FTN77,L
REAL FUNCTION SVEL(S,T,P0)
C*******************************************************************
C SOUND SPEED SEAWATER CHEN AND MILLERO 1977,JASA,62,1129-1135
C UNITS:
C       PRESSURE        P0       DECIBARS
C       TEMPERATURE     T        DEG CELCIUS (IPTS-68)
C       SALINITY        S        (PSS-78)
C       SOUND SPEED     SVEL     METERS/SECOND
C CHECKVALUE: SVEL=1731.995 M/S, S=40 (PSS-78),T=40 DEG C,P=10000 DBAR
C*******************************************************************
EQUIVALENCE (A0,B0,C0),(A1,B1,C1),(A2,C2),(A3,C3)
C
C   SCALE PRESSURE TO BARS
      P=P0/10.
      SR = SQRT(ABS(S))
C S**2 TERM
      D = 1.727E-3 - 7.9836E-6*P
C S**3/2 TERM
      B1 = 7.3637E-5 + 1.7945E-7*T
      B0 = -1.922E-2 - 4.42E-5*T
      B = B0 + B1*P
C S**1 TERM
      A3 = (-3.389E-13*T+6.649E-12)*T+1.100E-10
      A2 = ((7.988E-12*T-1.6002E-10)*T+9.1041E-9)*T-3.9064E-7
      A1 = (((-2.0122E-10*T+1.0507E-8)*T-6.4885E-8)*T-1.2580E-5)*T
     X     +9.4742E-5
A0 = (((-3.21E-8*T+2.006E-6)*T+7.164E-5)*T-1.262E-2)*T
X     +1.389
A = ((A3*P+A2)*P+A1)*P+A0
C S**0 TERM
C3 = (-2.3643E-12*T+3.8504E-10)*T-9.7729E-9
C2 = (((1.0405E-12*T-2.5335E-10)*T+2.5974E-8)*T-1.7107E-6)*T
X     +3.1260E-5
C1 = (((-6.1185E-10*T+1.3621E-7)*T-8.1788E-6)*T+6.8982E-4)*T
X     +0.153563
C0 = ((((3.1464E-9*T-1.47800E-6)*T+3.3420E-4)*T-5.80852E-2)*T
X     +5.03711)*T+1402.388
C = ((C3*P+C2)*P+C1)*P+C0
C SOUND SPEED RETURN
SVEL = C + (A+B*SR+D*S)*S
RETURN
      END
```

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