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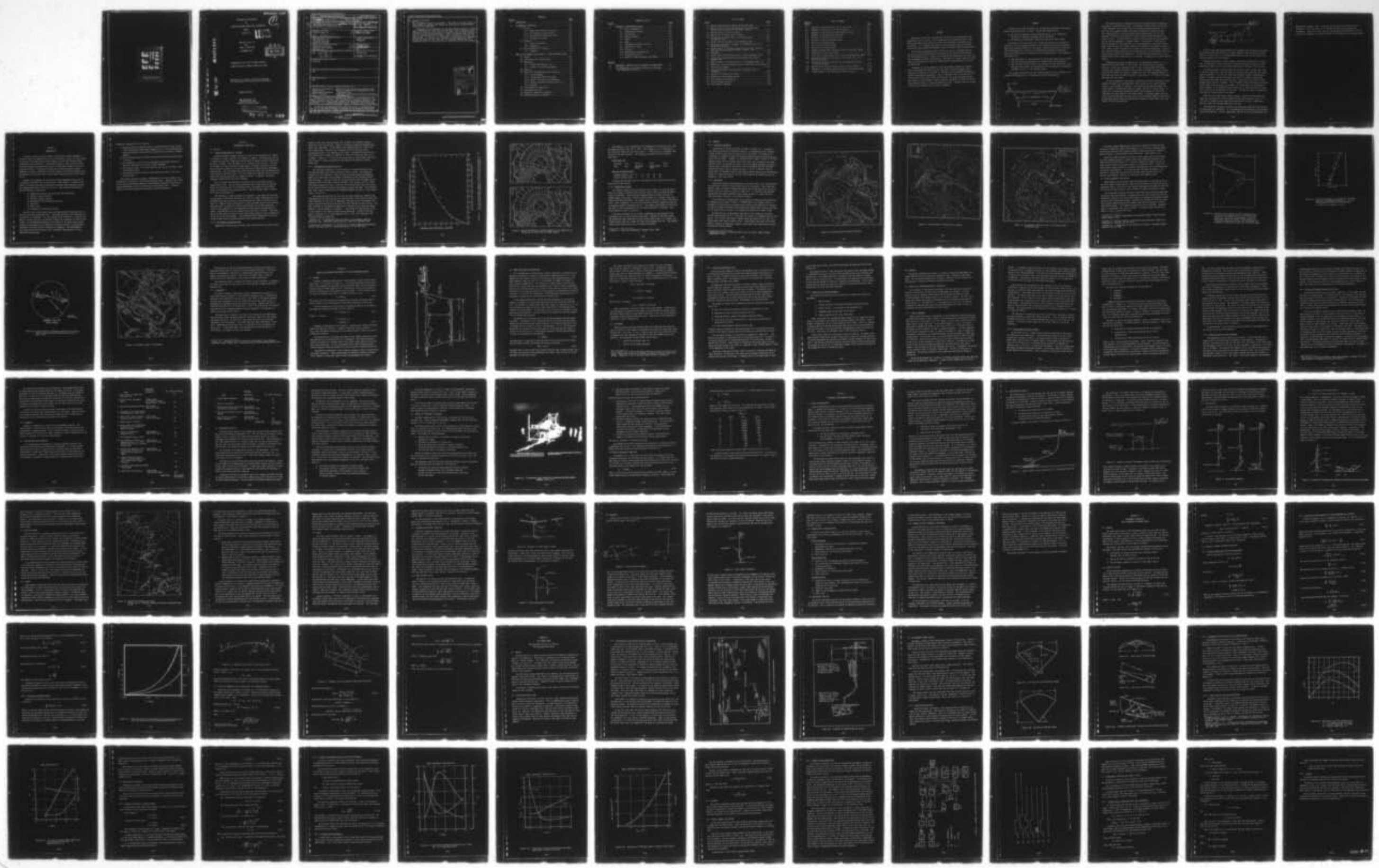

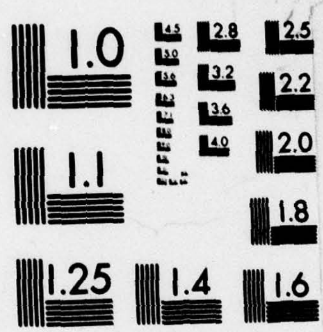

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DEPLOYMENT AND RETRIEVAL OF LINEAR HYDROPHONE ARRAYS AND SEISMOMETERS UNDER ARCTIC ICE

SHELTON M. GAY, JR.
AND
JOHN. J. NELLIGAN

SEPTEMBER 1976

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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20. Abstract (Continued)

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Methods are studied for placement and retrieval of instrumentation from beneath the Arctic ice pack. The instrumentation considered consists of long, linear hydrophone arrays (seismic arrays) and ocean-bottom seismometers and gravimeters. It is assumed that operations are conducted from an ice-locked ship having both complete oceanographic support and cable handling capabilities.

An inverted two-legged mooring (by which the array is suspended beneath the ice in a horizontal position) is selected as the preferred configuration for the hydrophone array. Methods for installing the suspensions and array, and their subsequent recovery are developed. The effect of current, depth and array length are examined with respect to system forces, and performance trade-offs are identified.

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SUMMARY

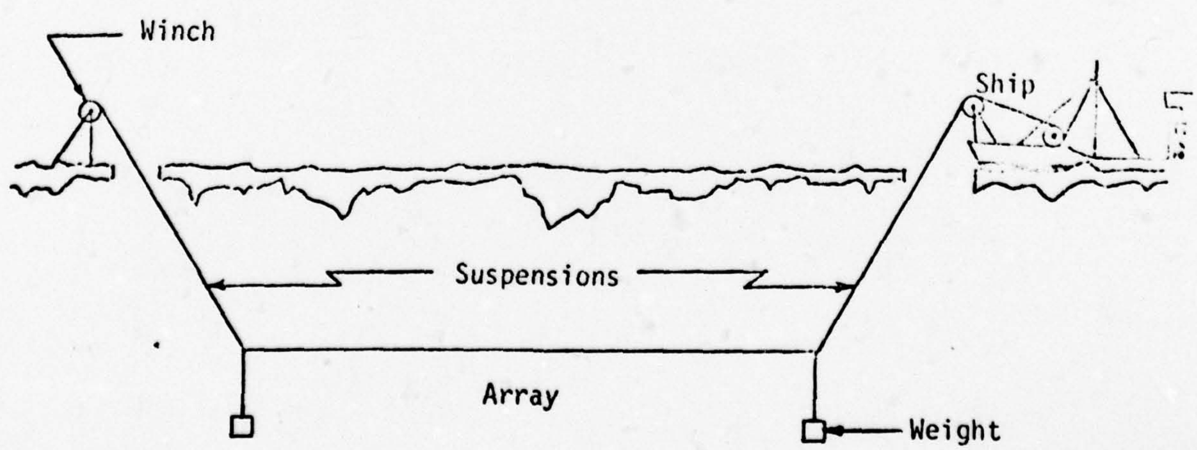
A study has been made of methods for configuring two different measurement systems beneath the Arctic ice pack. The systems considered are:

- Horizontally disposed, linear hydrophone arrays, up to 10,000 feet (3,048 m) in length and suspended in the mid-depths.
- Seismometers or gravimeters installed on the Arctic Ocean bottom.

The purpose of the study has been, through consideration of alternative approaches, to test concept feasibility and to define the preferred conceptual design and deployment method for each system. Emphasis was placed on the problems of deployment and retrieval of configurations meeting the operational constraints particularly as imposed by the ice-packed surface. The fundamental assumptions are:

- that operations are conducted from an ice-locked research vessel having full environmental measurement and equipment handling capability,
- that the ship, locked in Arctic ice, may drift slowly over shelf, slope and deep water basins, and measurements will be conducted for extensive periods of time (i.e., for several years).

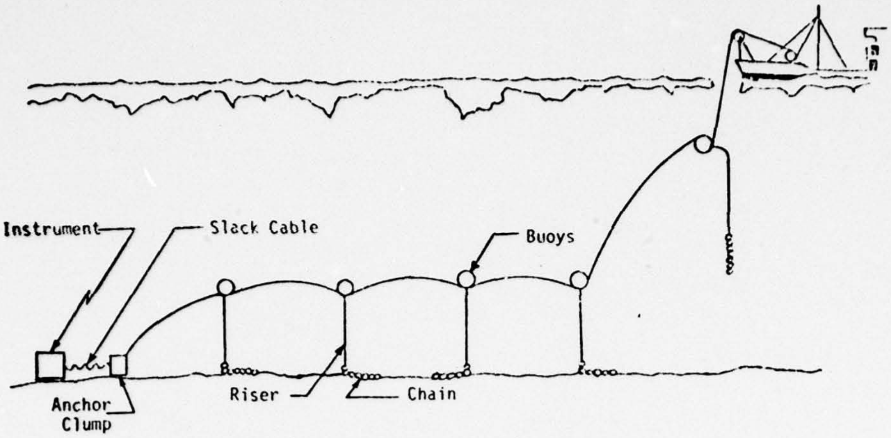
The <u>in situ</u> configuration of the linear acoustic array is conceived as an inverted two-legged moor, as illustrated in the following sketch:



The primary problem in deployment consists of establishing the suspension point that is remote from the ship. The approach selected consists of passing a light messenger line from the ship to the remote location and using it to haul the array suspension member into position beneath the remote ice hole. This method comprises a gravity-powered glider (Hydro-Glider) to carry the messenger from the ship ice hole to an acoustic beacon suspended beneath the remote ice hole. The Hydro-Glider is caused to spiral about the beacon support line so that the messenger is thereby snared. The messenger is then used to draw the suspension cable under the ice to the remote hole. The array is then drawn under the ice by the remote suspension to establish the desired configuration. Under certain circumstances, to avoid overstressing components, a part of the remote-end weight may need to be transported over ice, and attached after the array has been drawn to the remote hole. In this case the same portion of the remote weight would be detached prior to recovery. Recovery is otherwise straightforward.

A Rogallo-wing design is suggested for the Hydro-Glider because it is inexpensive and may be stored in small space. The glider would be launched, under-ice, at the ship, deploying light line as it glides toward the beacon. A simple, self-contained guidance system is used to provide directional control countering the effects of current, assymmetries, etc. The suggested design is only about one meter (3.4 feet) long with a wing span of 1 1/2 meters (4.9 feet) when the wings are spread.

For the seismometer or gravimeter, examination of several approaches to the problem of recovering a bottomed device led to selection of a cable tethered system. The instrument is lowered to the bottom and an anchoring weight (or shaped anchor) is established nearby to counter the pull in the main cable. A slack line is established between the anchor and instrument to isolate the instrument from the dynamics of the cable system. A slightly buoyant cable is used, but the height above the ocean floor is controlled by means of riser lines to the lower ends of which are attached short lengths of small chain, as illustrated in the following sketch.



Relative range and bearing between the instrument and ship must be monitored continuously and a plot maintained to detect danger of over-laying of the cable due to a circular drift. An interrogatable acoustic source could provide slant range and bearing, for this purpose.

Although the cable is slightly buoyant, the overall configuration is heavy. This is important in order to maintain a steep cable angle at surface, as indicated by the sketch, so as to not abraid the cable on the edge of the ice hole.

The time-on-bottom is determined by the length of cable and the drift rate of the ice-locked ship. When the supply of cable has been exhausted, the system must be recovered. It is at this point that the heavy system is advantageous. Ballast is dropped from the instrument such that it is slightly buoyant and floats above the anchor (or anchoring clump). The anchor (or clump) is either dragged across bottom, or dropped. The instrument is then towed above the bottom by the cable while the chains are dragged. If a chain snags an outcropping or other obstacle, it is broken away by the cable pull as the riser line will have only a fraction of the strength of the cable. The drag is minimal in comparison with that of a cable laying on the bottom.

When the last height control tether reaches a position directly below the ship, the instrument will float alongside the now nearly vertical cable. At this point it should be made negatively buoyant again so that it hangs below the last tether for recovery through the ice hole.

The information necessary to control the deployment, operation and recovery of the systems was considered. All instrumentation, handling gear and procedures are state-of-the-art. The only development required is for the Hydro-Glider and

Hydro-Glider automatic pilot. These are not considered to be high risk developments. Full scale tests of the Hydro-Glider and snaring system are recommended. Small (1/4) scale tests of the deployment and recovery of the two systems are recommended to prove procedures, data requirements and communications.

Section 1

INTRODUCTION

Scientific studies of ocean acoustic and sea-floor seismic phenomena in the Arctic Basin are impeded by the lack of open water on which to situate buoys for marking and supporting subsurface elements, and for functioning as data accumulators and transmitters. Instruments lowered by cable to the sea-floor are soon dragged across the bottom as the ice cover drifts under the stress of winds and currents. Deployment of horizontally disposed high-gain (multi-hydrophone) arrays of significant aperture presents a significant problem since emplacement by conventional means could require trenching across several miles of ice.

Methods for deployment and retrieval of linear hydrophone arrays and of seismometers from under the ice are explored in this report. A number of concepts for accomplishing these functions were examined and winnowed to produce the recommended methods discussed in the text. The selections were based on the considerations listed below:

- Information necessary for control of the installation
- Logistic support required
- Technical support required
- Development required and technical risk
- Total cost
- Risk of loss
- Consequence of malfunction or loss

The first part of this report deals with the problem of deploying and retrieving the linear hydrophone array. The second part deals with deployment and retrieval of a seismometer. For each problem, brief discussion is given of the several concepts explored, and the major reasons for acceptance or rejection are stated. The recommended approaches are developed to the extent where primary problems of implementation are identified, and where technical and operational solutions to the more critical functions are suggested. The developmental, test and evaluation work necessary for a successful implementation is also identified and discussed.

Assumptions fundamental to the study are:

- The operations are conducted from an ice-locked research vessel having a full environmental measurement capability (e.g., current measurements, bottom photography, bottom sampling, high-accuracy navigation, computer support).
- The technology exists for establishing and maintaining openings (holes) in the ice.
- The seismometer is to be left on the bottom for extended periods of time for investigation of natural seismic phenomena.
- The research vessel, in drifting with the ice, may be over shelf, slope or deep basin waters.
- The operations may be conducted over extensive periods of time (i.e., several years).

The handling (winching, storage, overboarding) of the two systems is not considered to constitute a limiting technological factor. Moreover, the sizing of the handling equipments depends on the performance parameters selected for system implementation and the capabilities of the support ship. Sizing and selection of these equipments was therefore considered premature.

Section 2

ENVIRONMENTAL CONDITIONS

2.1 SEA ICE

2.1.1 General Description of Ice Pack

The Arctic Ocean is mostly covered by a layer of ice averaging 3 to 4 meters in thickness in winter and some 2 to 3 meters in summer. In places where the ice is crushed by the wind, ridges may form and reach 10 meters or more in height and 50 meters in depth. This vast cover of ice is known as the ice pack. This mass of ice moves at a very low rate of speed, about 1 mile/day, from east to southwest, eventually finding its way out into the North Atlantic between Spitsbergen and Greenland. The ice blanket that covers the Arctic Ocean and its adjacent seas varies greatly from year to year. The ice boundary may fluctuate several hundred miles about the mean position in a number of places. In general, the summer coverage is about 60% of the winter coverage.

Sea ice results from freezing of sea water which, with normal salinity, takes place at $-2^{o}C$. The ice from the sea water has a lower salinity than the water itself because part of the dissolved salts, particularly the chlorides, escape as brine during the freezing process. Sea ice includes freely floating drift ice and shorefast ice.

The difference in density between ice and water is such that only one-fifth to one-seventh of the total thickness of a level or slightly hummocked ice field protrudes above the sea surface, and one-third to one-fifth of the total thickness of a ridged or markedly hummocked ice field protrudes above the sea surface. The underside of the pack ice reflects approximately its surface topography. A field of high hummocks will be compensated by long matching protruberances beneath. Protruberances may reach depths of 40 to 60 feet, or larger. The losses due to surface melting of polar ice are replenished primarily by the accumulation of new ice on the under surface. This growth partially compensates for the 20 or more inches lost by ablation from the surface during one year.

2.1.2 Ice Thickness and Variability

Summarizing coincident laser profiler data from the top side of the ice and submarine sonar data from the botton side, Diachok[1] has presented valuable statistics of sea ice profiles. There is a definite correlation between ridge height and ridge depth. For the median case, ridge heights are 1 meter high and 5 meters deep. There will be 4 ridges/km with this property with a corresponding total of 14 ridges/km of all sizes. The spatial variability for the average total of number of ridges/km is 2 to 10 in the winter and 2 to 6 in summer. Figure 2.1[2] is a plot of the variability of ridge height statistics, while Figure 2.2[1] gives a geographical and seasonal indication of spatial variability.

2.1.3 The Mechanical Properties of Ice

The continuous formation of ice by freezing is counter-balanced by very effective processes that reform and destroy the ice fields. The mechanical properties of ice (elasticity, plasticity and resistance against deformation, bending and compression) are of greatest importance in the interplay between these processes. Large ice fields are broken up rapidly from the edges, by the combined action of the wind, waves and periodic tidal currents, and in a short time become separate ice floes. With the aid of strong winds they are piled up by the large horizontal pressures and pushed one above the other. The resultant mass, when finally covered with snow, cemented together and built up into several layers, is pack ice.

The mechanical properties of ice, like its other properties, depend on the temperature and salinity, but due to the multiplicity of ice forms and conditions these determine only the order of magnitude, and there may be considerable variations caused by the special structure of the ice floe and its past history. The most important of the mechanical properties is the elasticity, given by Young's modulus E, and the modulus of rigidity μ. Ice, being of a crystalline nature, is not isotropic with regard to these stress properties. Typical values for thin ice rods are: $E = 9 \times 10^{10}$ dynes/cm^2 and $\mu = 3.36 \times 10^{10}$ dynes/cm^2, the Poisson constant is about 0.36.

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[1] Diachok, O.I., "A Preliminary Empirical Model of Low-Frequency Under-Ice Reflection Loss," NAVOCEANO Technical Note No. 6130-3-73, September 1973.

[2] Tucker, W.B. and Westhall V.S., "Arctic Sea Ice Ridge Frequency Distributions Derived From Laser Profiler," AIDJEX Bulletin No. 21, 171-180, 1973

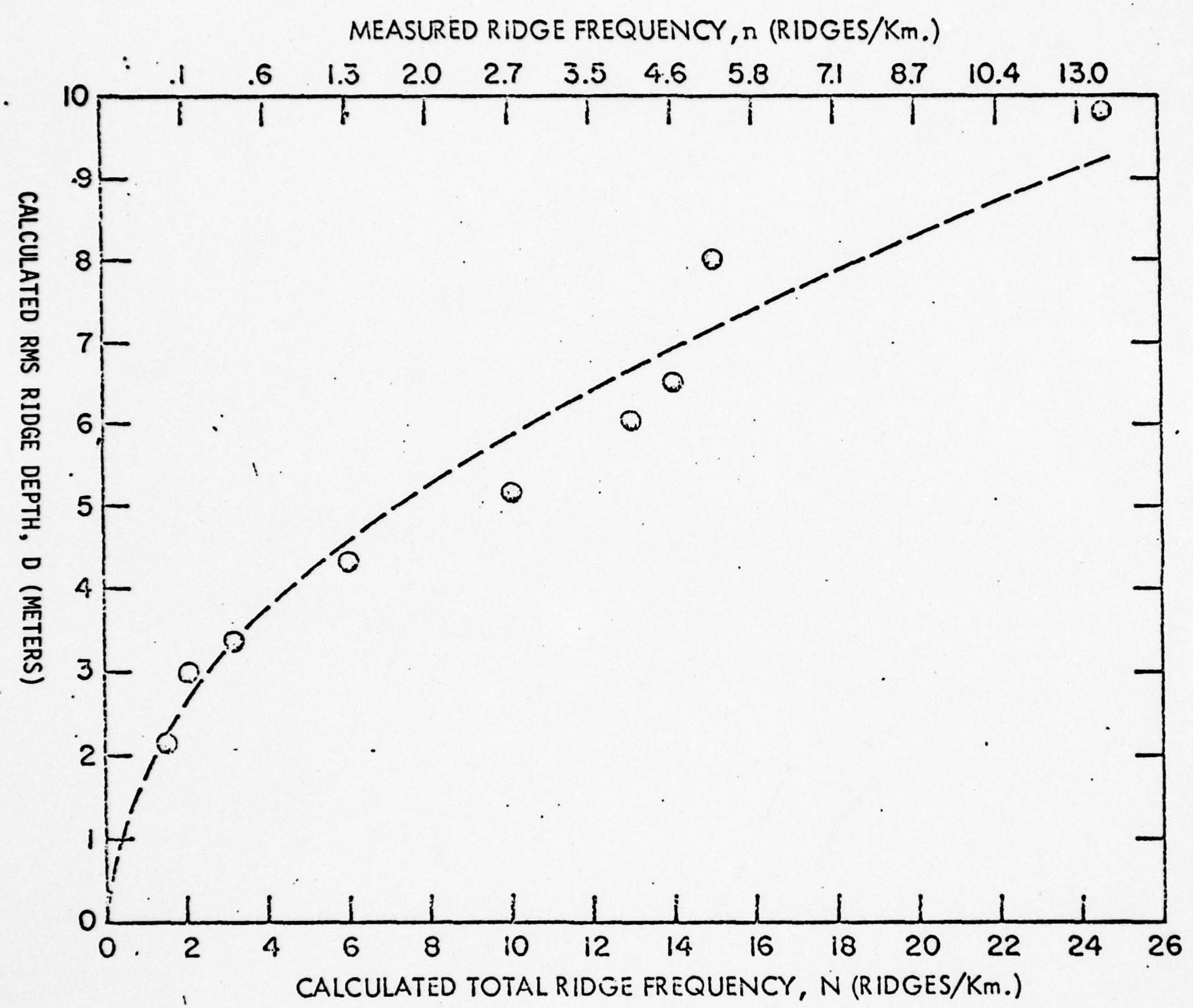

Figure 2.1 Empirical Relationships Between the Measured Ridge Frequency, n, the Calculated Total Ridge Frequency, N, and the RMS Ridge Depth, D

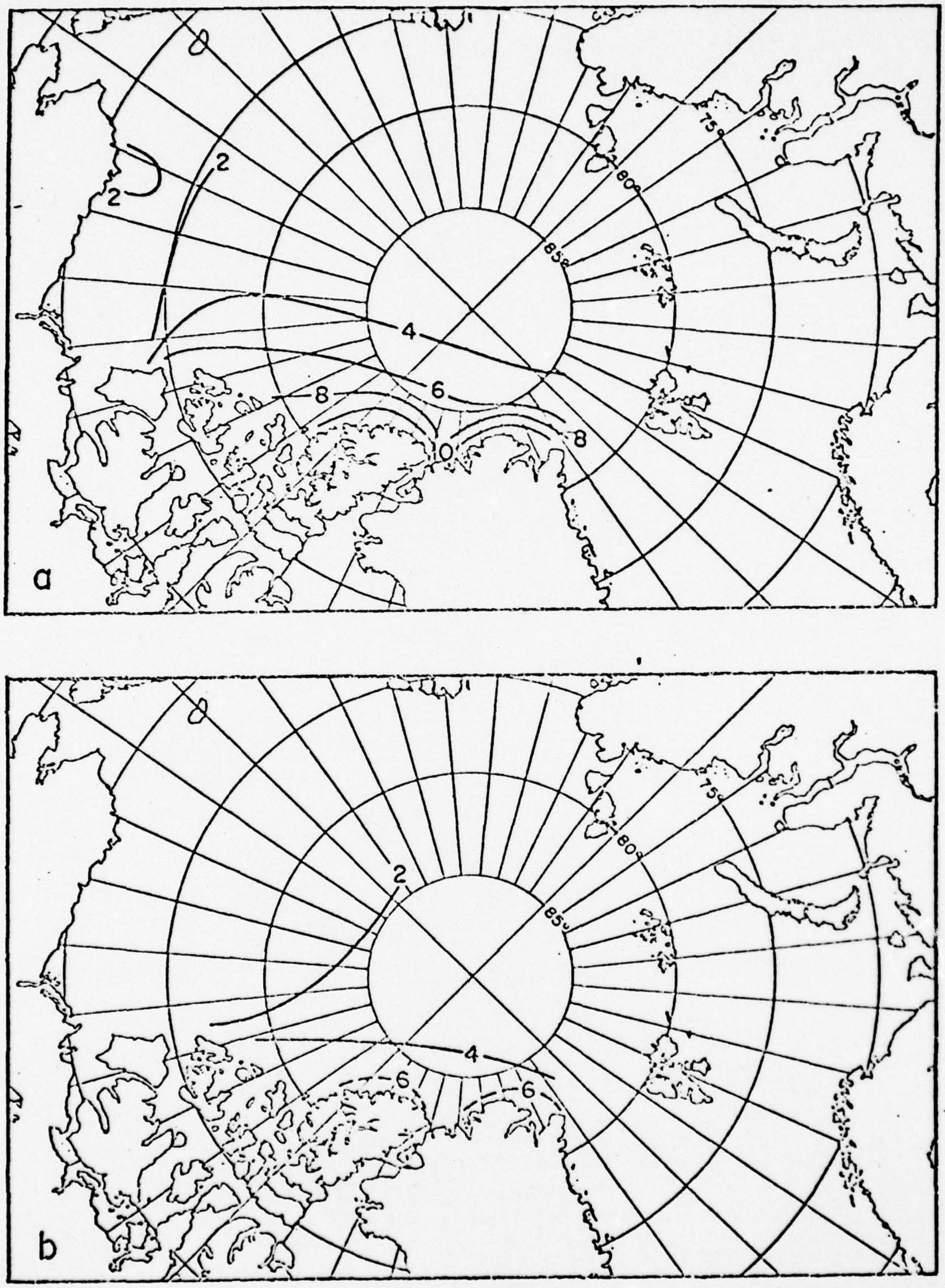

Figure 2.2 Spatial Variability of Ridge Frequency (n) in Ridges per Km During the (a) Winter and (b) Summer Seasons

The strength of sea ice depends on the temperature--increasing by 45%, when the temperature goes from -3°C to -30°C. The strength of ice is important in calculating the loads that can be put upon it. Fresh water ice is stronger than sea ice of the same thickness. The following are empirical data[3] based on experience:

Fresh water ice:

Thickness:	4 cm	10-12 cm	15 cm	45 cm
Load:	Man	Galloping Horse	Heavy-loaded Truck	Train

Also for landing aircraft:

Minimum thickness (cm):	16	24	32	39	45
Aircraft weight (tons):	2	5	10	15	20

To carry the same load, the ice in the center of the Arctic basin must be two to three times thicker.

2.1.4 Floating Ice Islands

Ice islands originate from an extensive area of shelf ice along the North Coast of Ellesmere Island and from a similar area of shelf ice along the North Coast of Greenland. Tides and waves produced either by seismic activity or sudden changes in barometric pressure cause the shelf ice to break loose, thus forming the floating islands. Ice islands vary in size to as large as 300 square miles. Their topography is rolling and relatively uniform, contrasting with the surrounding ridged and hummocked sea ice. The islands extend about 40 feet above the level of the surrounding sea ice and average 200 feet in thickness, some being reported as thick as 250 feet.

The rate of movement of ice islands is dependent on the movement of the surrounding sea ice, ocean currents, and winds. Because of their deep draft, the islands are more responsive to ocean currents than winds. As a result, the islands usually move at a slower rate than the surrounding sea ice. The observed rate of drift varies from 1.0 to 1.3 nautical miles/day.

[3] Defant, A., "Physical Oceanography," Permagon Press, 1960.

2.2 CURRENTS

2.2.1 Surface Circulation

The patterns of surface currents are shown in Figure 2.3[4]. In general, the surface circulation in the Arctic Ocean is a slow westerly drift, forming a large clockwise gyral over the major part of the region. This pattern of circulation is largely the result of the anticyclonic system of winds which prevails over the region. However, as revealed by the irregular courses of drifting icebound vessels and ice islands, the surface flow, when considered over short periods of time, is extremely variable. The drift records indicate a resultant rate of about 1 mile/day in the region north of the North American Continent and Eastern Siberia, and an increase to about 1 1/2 to 2 miles/day from the region north of Severnaya Zemlya to the opening between Greenland and Spitsbergen. Figure 2.4[4] shows the tracks of the most significant drift expeditions and ice movements in the Arctic Ocean.

2.2.2 Subsurface

Some of the general characteristics of subsurface flow can be inferred from the distribution of water masses identified by T-S structure. These show that Atlantic water is found at intermediate depths (100 to 500 meters) at nearly all parts of the Arctic Ocean as shown in Figure 2.5[4]. It should be realized that strong winds may modify temporarily the current regions in a short period of time and intermix the water to considerable depths.

Ice stations and ice-bound ships move generally westward and southward with an average drift of about 2 km/day. In AIDJEX (Arctic Ice Dynamics Joint Experiment) the objective was to measure water stress on the underside of the pack ice and to provide information on how water drag behaves under various conditions of ice speed relative to water, ice roughness and stability of water column.

An important set of measurements required in this program was the water current profile below the ice. Frictional loss occurs in a boundary layer of two parts: (1) a surface layer about 2 meters thick just below the ice, and (2) a second Ekman layer about 25 meters thick. In the Ekman layer both friction and earth's rotation are important, leading to the Ekman spiral description of water currents and current gradient.

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[4] "Oceanographic Atlas of the Polar Seas," Part II, Arctic, 1958, US Navy Hydrographic Office.

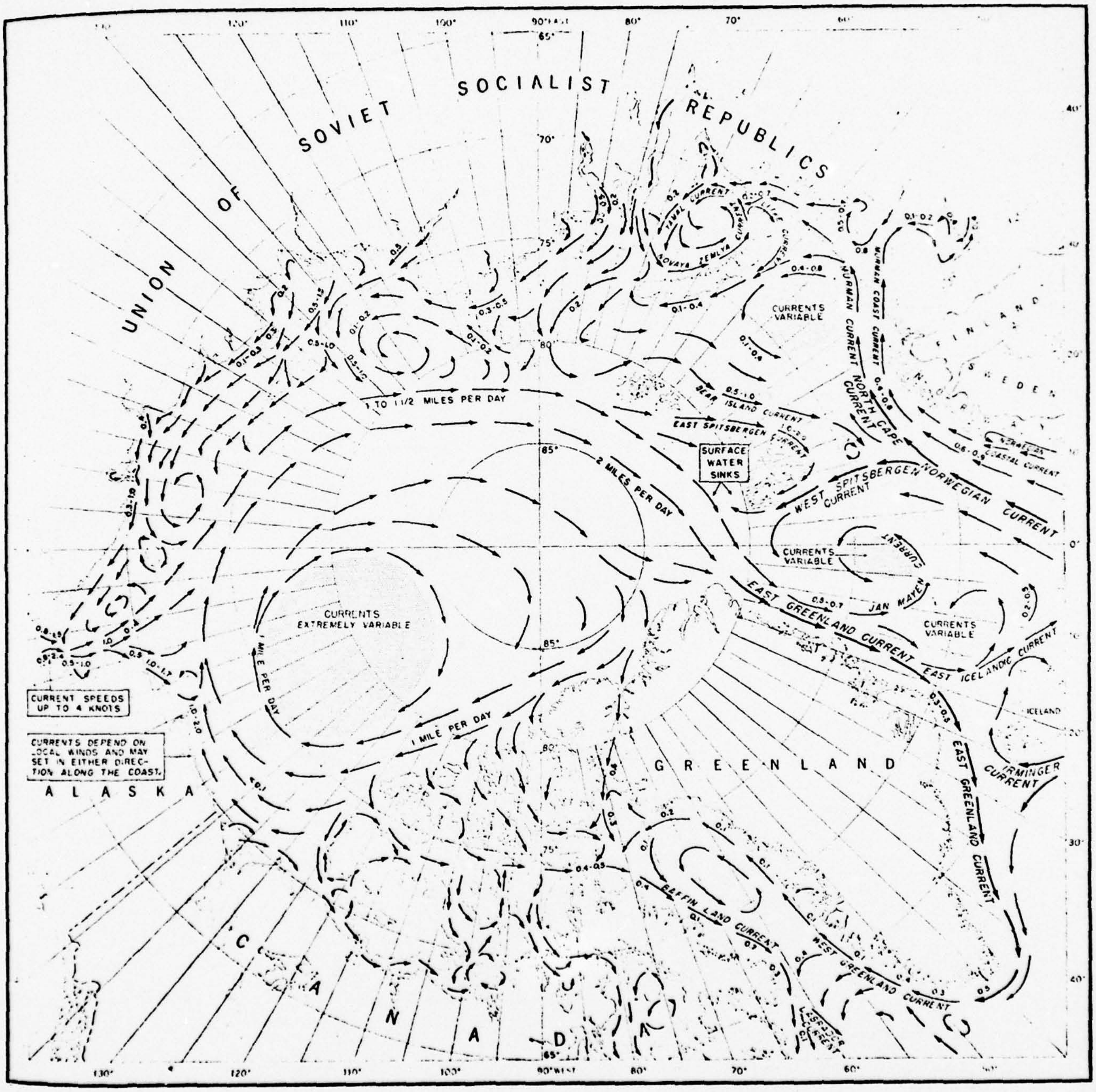

Figure 2.3 General Surface Circulation (Knots)

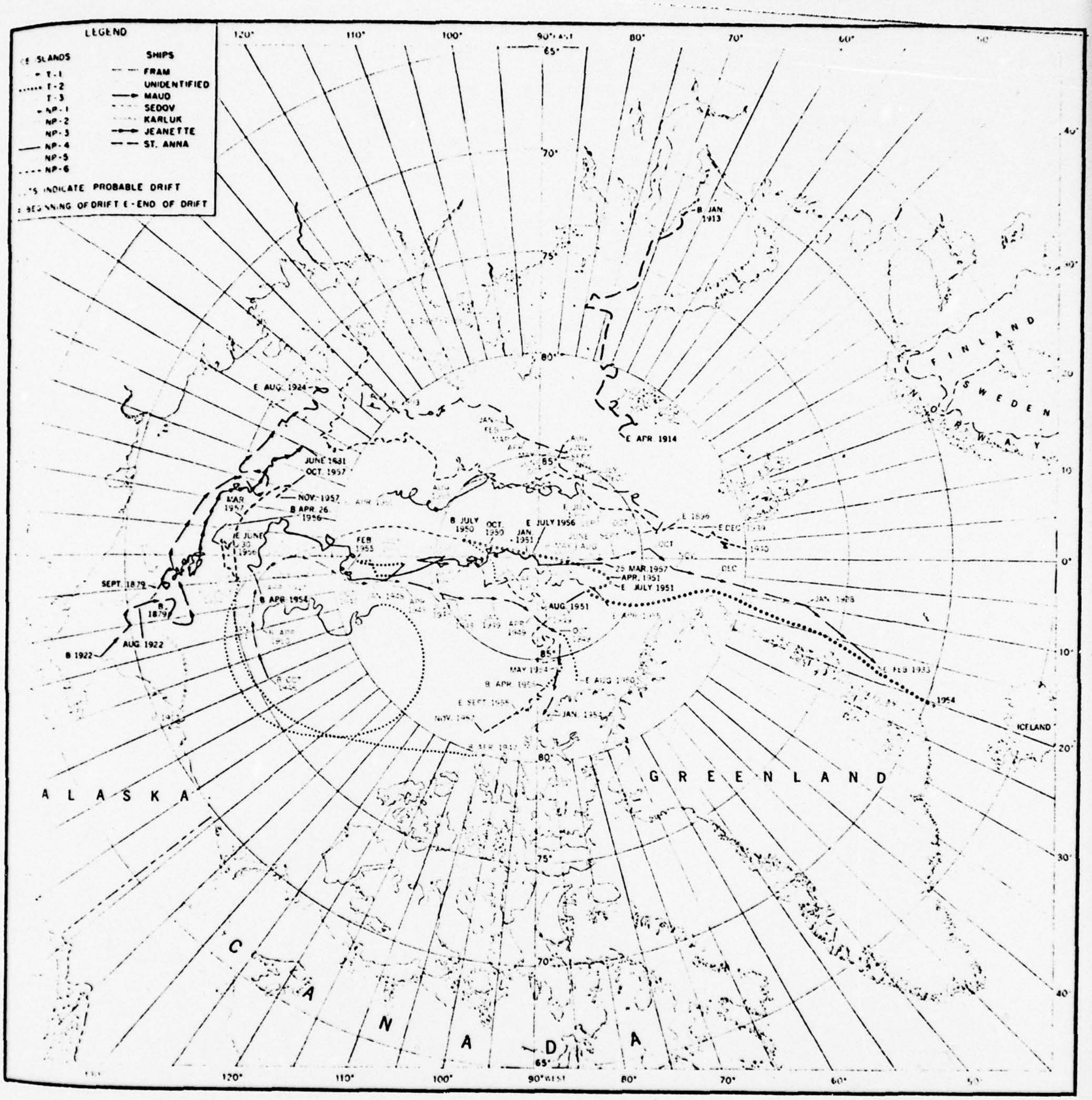

Figure 2.4 Major Drifts of Vessels and Ice Islands

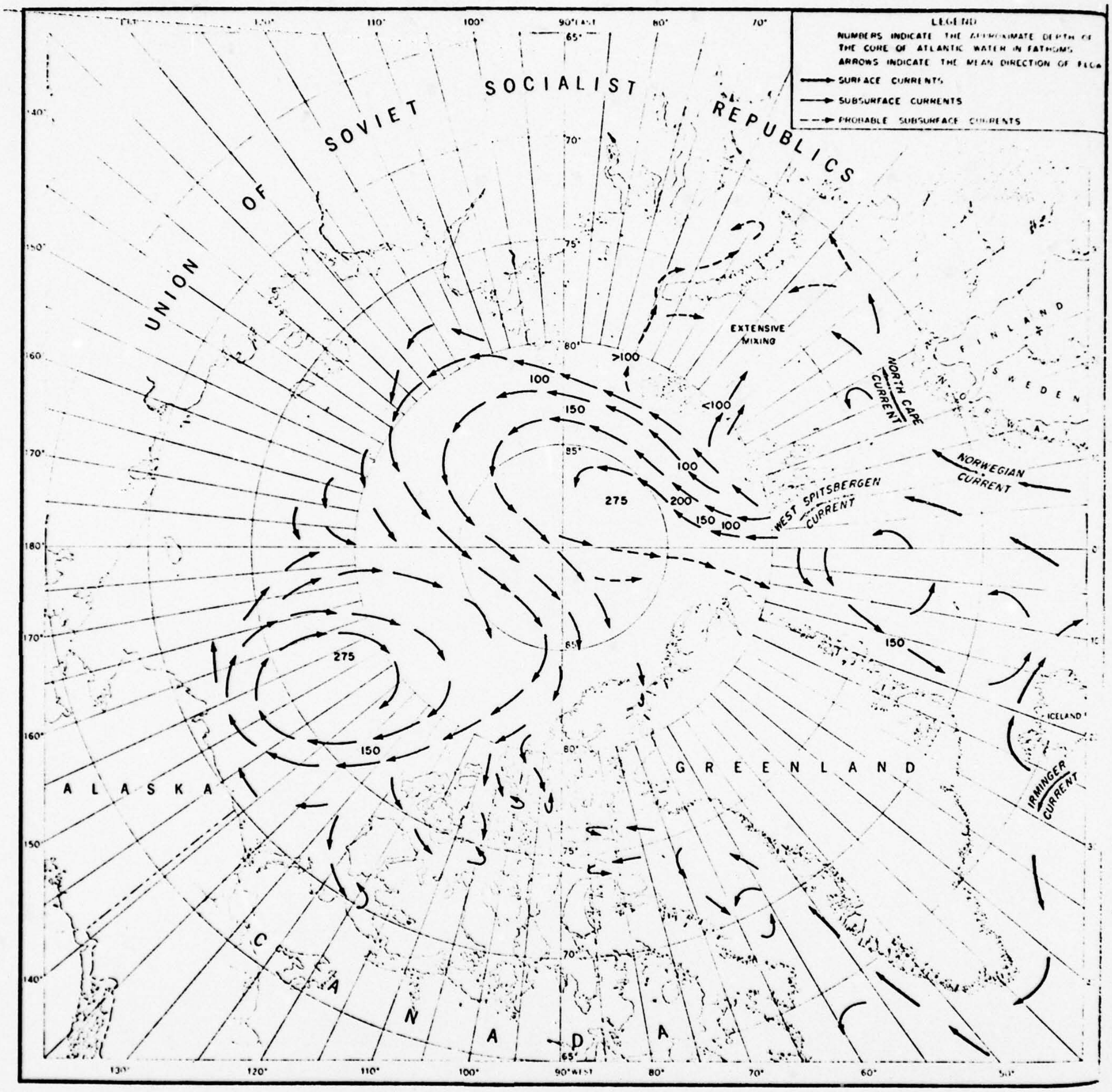

Figure 2.5 Circulation of Atlantic Water in the Arctic Ocean and Adjacent Seas

An unusual current phenomenon was observed at depth associated with the existence of baroclinic eddies with diameters of 10 to 20 km. Transient under-currents were observed which attained speeds of about 40 cm/sec at a depth of about 150 meters, ranging between 50 and 300 meters. (See Figure 2.6[5].)

The Arctic eddies contrast with those in other oceans which are generally of larger diameter and have a surface rather than subsurface maximum of horizontal velocity (see Figure 2.7[6]). The Arctic eddies are roughly circular in plan and both clockwise and counterclockwise circulations occur. Figure 2.8[5] shows current vectors plotted at a depth of 100 meters as the ice drifted across an eddy of 10 km diameter. It is believed that the eddies originate in the baroclinic instability associated with the mean shear between Pacific and Atlantic water masses intruding into the Arctic from opposite sides.

2.3 ARCTIC BATHYMETRY AND GEOLOGY

Water depths vary from about 2,000 fm (3,660 meters) in the deep basins of the Arctic Ocean to mean depths of about 25 fm (43 meters) on vast areas of the continental shelf. Figure 2.9[7] shows generalized bottom topography including the location of the major features such as basins, plateaus and extensive ridges.

The broadscale structural features in the Arctic are the basins underlying the Arctic Ocean and Greenland - Norwegian Seas, the fold systems crossing the continental platforms and coastal plain areas, the emerged and submerged coastal plains and the continental shields. The basins in the Central Arctic are separated by the Lomonosov Ridge which connects with the fold systems in Siberia and Northern Canada. The irregular-shaped basin of the Greenland - Norwegian Seas is a continental-type block structure. A volcanic chain, of which Jan Mayen is a part, crosses this basin.

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[5] Hunkins, K., "Physical Oceanography in the AIDJEX Program," Naval Research Review, NAVSOP - 510.

[6] Webster, F., "Vertical Profiles of Horizontal Ocean Currents," Woods Hole Oceanographic Institute, Ref. No. 69-31.

[7] Johnson, G.L., "Morphology of the Eurasian Arctic Basin," The Polar Record, Volume 14, No. 92, 1969.

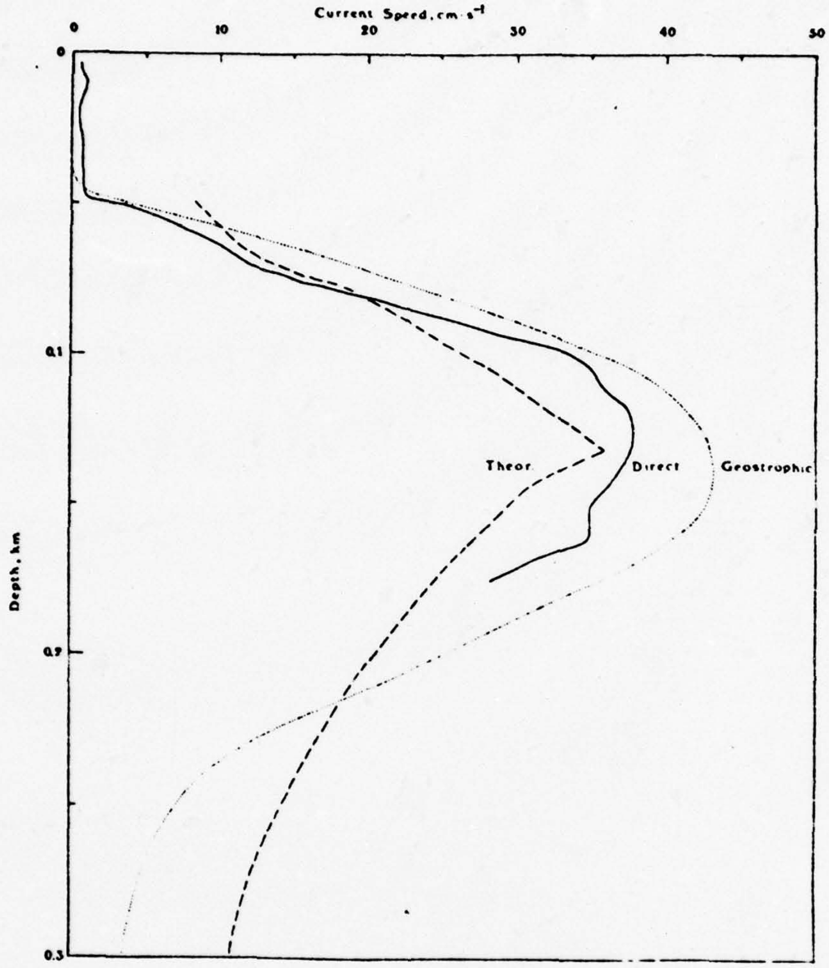

Figure 2.6 Current Profiles Through an Arctic Mesoscale Eddy. The solid line represents direct current meter observations, the dotted line represents calculated geostrophic velocities between closely-spaced salinity and temperature profiles, and the dashed line is based on a theoretical baroclinic instability model.

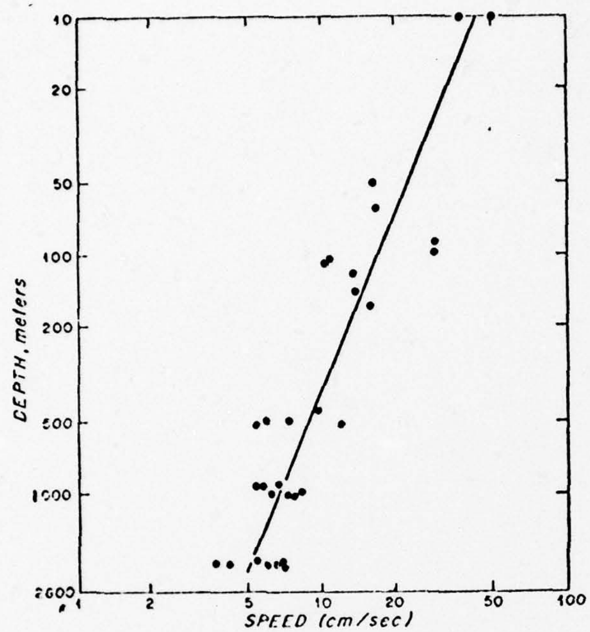

Figure 2.7 Profile of Log Speed vs Log Depth for 30 Records From Site D (Northwestern Atlantic). The line Fitted Through the Points has the Equation

$s = 670z^{0.4}$ (s in cm/sec, z in cm).

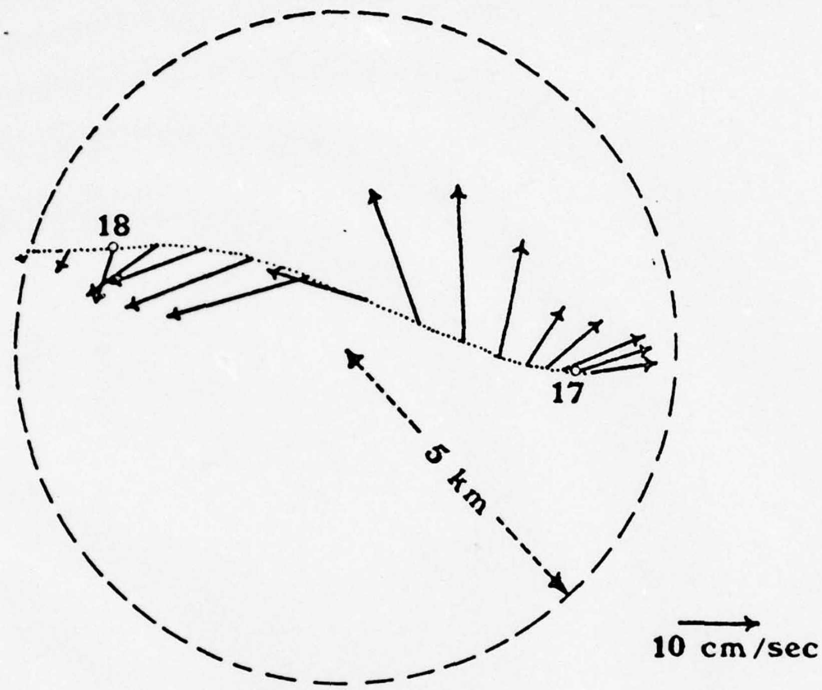

Figure 2.8 Current Vectors at 100 meters Depth Across an Arctic Mesoscale Eddy Observed During Rapid Ice Drift in April, 1972.

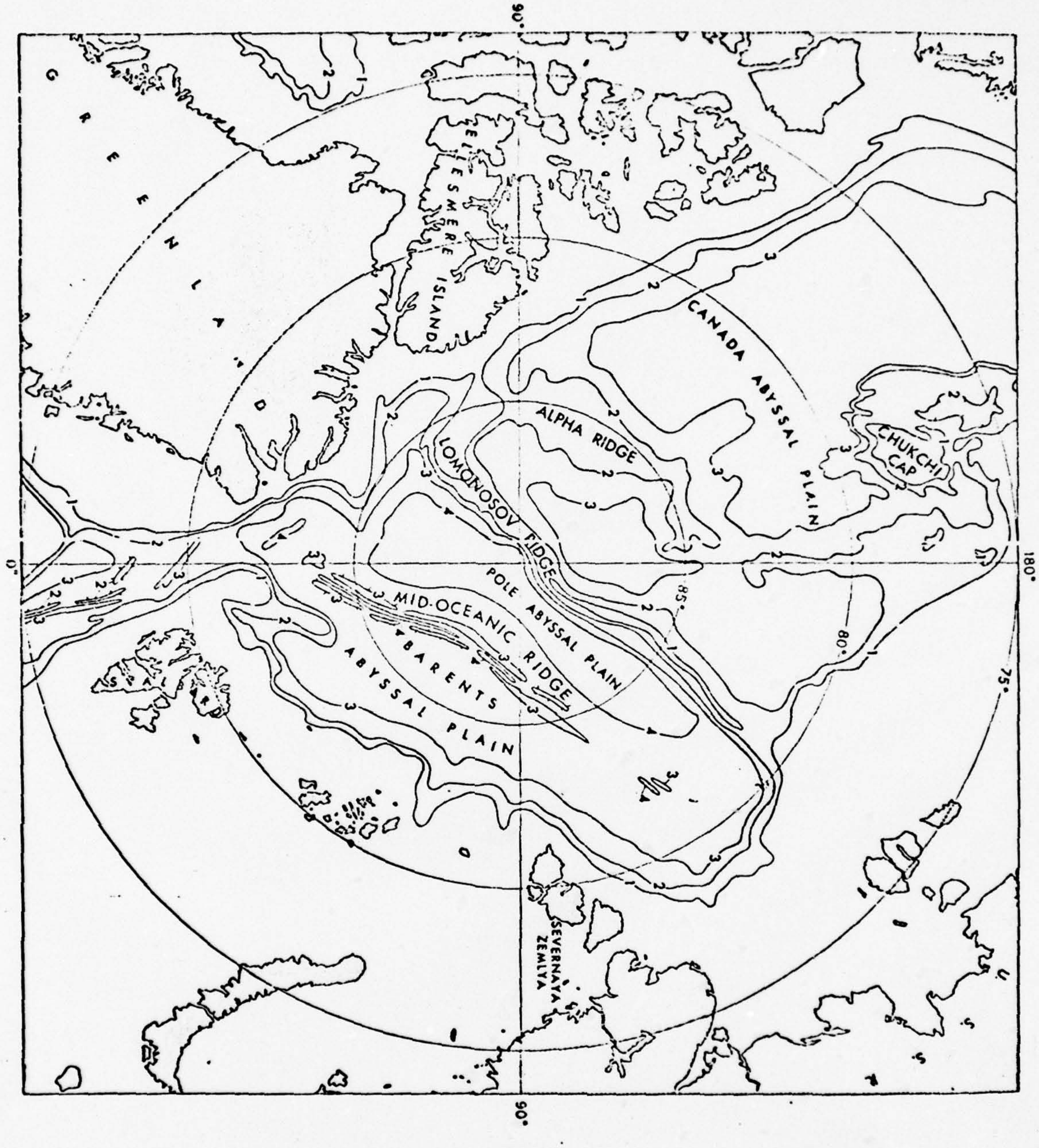

Figure 2.9 Bathymetry (Depth in kilometers)

The major part of the Arctic Continental Shelf of Eurasia and Alaska is a submerged coastal plain or extension of the Continental Platform. This shelf, which is the broadest in the world, is approximately 600 miles wide in the Barents and Chukchi Sea sectors. The Arctic Continental Slope is sharply defined, having the appearance of fault scarps of major proportions.

The Continental Shelf, extending from Canada to past Greenland, is comprised of stable land masses, and was subject to little vertical movement during past geologic time.

2.3.1 Sediments[7,8]

The Arctic sediment is dominated by debris transported by glacial ice. A significant amount of sediment is derived from atmospheric dust. Sedimentation processess have covered the sea floor with a flat layer of terrigenous deposits. Sediment that accumulates on the Continental shelves of the central Arctic is transported to the deeper basins by turbidity currents. However, the bulk of turbidites consists of silt-size particles. Sand is well-sorted and fine-grained. Skeletons of marine organisms comprise another component of the sediments in parts of the central Arctic Basin.

This means that, in general, the floor of the basins will be dominated by muds mixed with harder inorganic materials, while the ridges will have rougher and harder materials. The basins will have about one km of unconsolidated sedimentary rock and basement. The ridges have only 300 to 400 meters of sediment. Sedimentation rates range from 1 to 3 mm/1000 yr over the Chukchi and Alpha areas. In the Canada Basin, the sedimentation rate of turbidites is 8 cm/1000 yr, the highest in the Arctic regions.

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[8] Clark, D.L., "Geological History of the Arctic Ocean Basin," from "Canada's Continental Margin," Memoir No. 4, Canadian Society of Petroleum Geologists, 1975.

Section 3

UNDER-ICE DEPLOYMENT AND RECOVERY OF LINEAR HYDROPHONE ARRAYS

3.1 GENERAL

A typical preferred configuration of a horizontally disposed linear hydrophone array is illustrated in Figure 3.1. In this configuration the horizontal force H that maintains the nominally *neutrally buoyant (NB) array and Vibration* Isolation Modules (VIMS) under tension is obtained by virtue of the weights W and the inclination A_0 of the support lines of length ℓ. If the support lines are neutrally buoyant, the force H is found from statics to be

$$H = W \text{ctn} A_0. \qquad (3.1)$$

The forces that cause the array to deviate from a stright line may be due to water currents or to slight departures from neutral buoyancy of the array.

The total separation X of the points of suspension depends on the depth Y, the angle A_0 and the array length S, and is given by

$$X = 2\ell \cos A_0 + S. \qquad (3.2)$$

Since $\ell = Y \csc A_0$,

$$X = 2Y \text{ctn} A_0 + S,$$

$$= 2Y (H/W) + S. \qquad (3.3)$$

Assuming, for purposes of this analysis, a maximum array length (including VIMS) of 10,000 feet (3,048 m), a depth of 1,000 feet (305 m), and H/W = 1 ($A_0 = 45^o$), the maximum separation of the suspension points could be as much as 12,000 feet (3.659 m).

The problem then is to deploy and recover arrays between suspension points separated by up to 2 nautical miles (3.7 kilometers). The remote suspension could be eliminated if a powered vehicle were used to apply tension to the outboard end of the array. As will be discussed later, this approach appeared counter-productive from the standpoint of noise, technical complexity and cost.

The problem of deployment is thus primarily reduced to that of establishing the remote suspension. Certain operational considerations should be treated first, however, as they have impact on both the deployment and recovery.

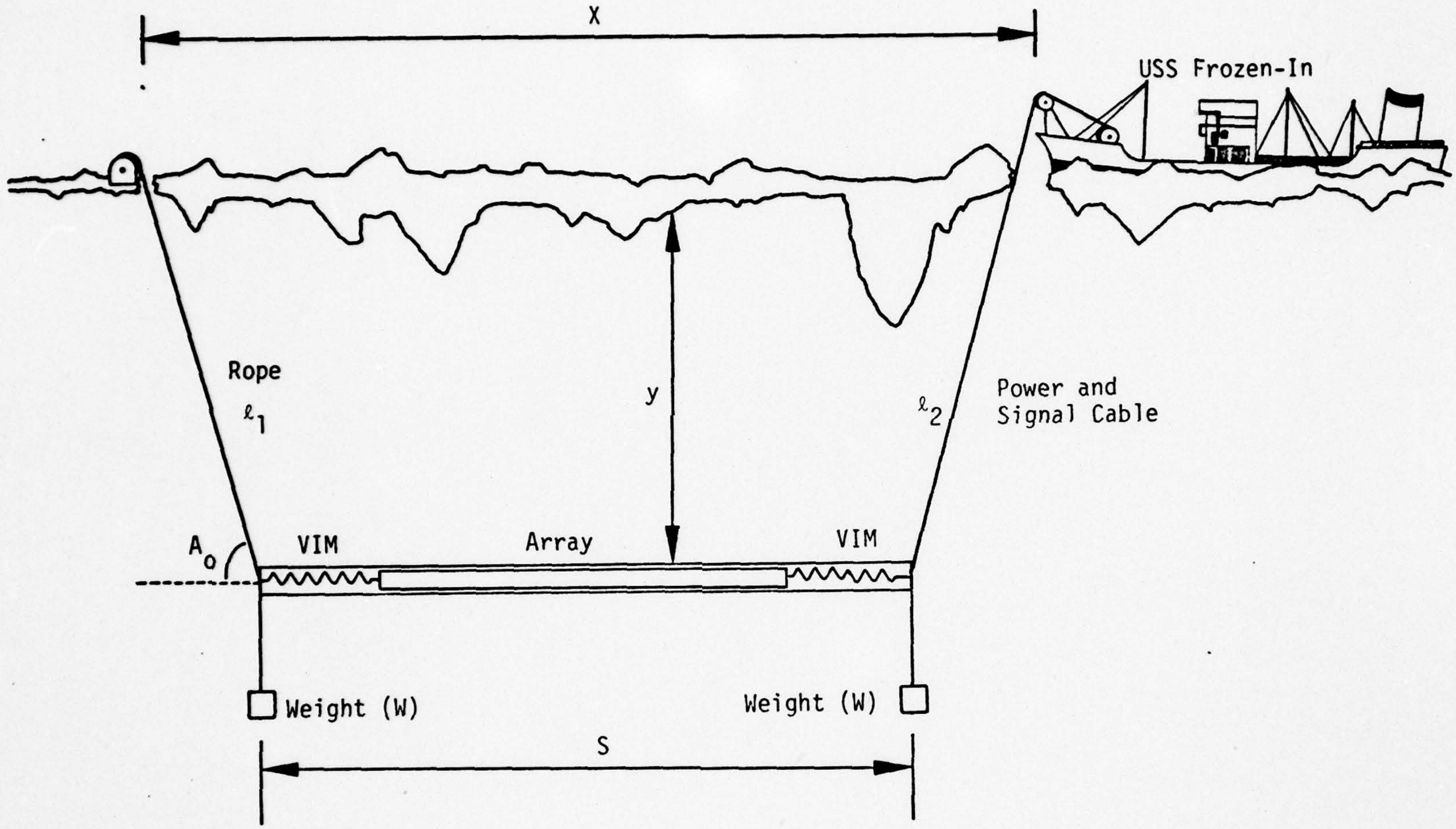

Figure 3.1. Typical Under-Ice Configuration for a Linear Hydrophone Array

3.2 SOME OPERATIONAL CONSIDERATIONS

It is assumed that a research vessel frozen in the Arctic ice pack will be equipped to establish a remote site and maintain communications with it. The remote site will require a winch to facilitate possible adjustments to the remote suspension rope (or cable) ℓ_1, as the distance X cannot be assumed to remain constant indefinitely. The formation of ridges, shears, and even the possibility of open-leads must be considered, and a certain range of adjustment provided to avoid the necessity for recovery of the array as a result of a short term shift in the relative positions of the suspensions, followed by a stabilized situation. It will be later shown that a winch (and other handling gear) will be needed to accomplish the installation and recovery also.

If the remote suspension ℓ_1 and the ship-end suspension ℓ_2 are of equal lengths, a decrease in X would only deepen the array and reduce the magnitude of H. An increase in X beyond some limit would require an increase in ℓ_2 (or ℓ_1) to avoid excessive stress on the array and would result in tilting the array relative to the horizontal. In this case, ℓ_1 (or ℓ_2) must be increased to again make the array horizontal. An active winch at the remote location thus appears to be an operational necessity.

An estimate of the maximum size of the tensioning weights required would be helpful. In Appendix A it is shown that for an array ballasted for neutral buoyancy to within the current state-of-the-art, the important deviations from a straight line will be due to current induced forces. If Z is the horizontal deflection of the center of the array under a uniform drag per unit length R (normal to the array axis), a conservative estimate of the maximum deflection is given by the equation for the parabola

$$Z = RS^2/8H. \qquad (3.4)$$

Assuming that it is desired to limit the ratio Z/S to one percent for the maximum anticipated current, an estimate of H may be found from

$$H/S = 12.5\ R. \qquad (3.5)$$

Available data on Arctic under-ice currents indicates that currents greater than 0.3 knots (15 cm/sec) will be encountered only rarely, even over the sills and passages into the Arctic basin.

The array is unlikely to be larger than 3 inches (7.6 cm) in diameter. This array will strum at a frequency of about 0.4 Hz. The Reynolds number will be about 7,500 for which a rigid cylinder drag coefficient C_R slightly greater than unity is found (depending on roughness). Experience with flexible cables indicates that strum can result in nearly a doubling of this value. A value of 2 is therefore selected* for C_R. Hence an estimate for R of 0.13 lb/ft (0.19 kg/m) is found. Using the above,

$$H/S \geq 1.625 \text{ lb/ft } (2.42 \text{ kg/m}).$$

If

$$S = 10^4 \text{ ft} = 3{,}048 \text{ m},$$

then

$$H \geq 16{,}250 \text{ lb} = 7{,}370 \text{ kg}.$$

And, for A_0 = 45 degrees,

$$W = H = 16{,}250 \text{ lb } (7{,}370 \text{ Kg})$$

This illustration is based on rather severe requirements. Relaxation of the performance requirements with respect tc array deflection, design current and array length results in significant reductions in the size of the tensioning weight and the tension across the array. A discussion of the trade-offs available is given in Section 3.9.

3.3 DEPLOYMENT

The most obvious (and the selected) method for deploying the array consists of passing a light leader or messenger line between the suspension points of the array. This line, in turn, is used to haul over other lines until one of adequate size and strength is available to haul the weighted array into position. The subsequent problem breaks into two parts:

1. Passing the messenger under ice
2. Control of the array deployment.

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*It is doubtful that strum of amplitude sufficient to result in a C_R of 2 will occur. This value is used as an extreme for purposes of establishing feasibility. Values of 1.2 to 1.6 are more likely to occur in practice.

3.3.1 Passing the Messenger Line

The most obvious method for passing the messenger line is to attach it to a self-powered housing (several of which have been developed) and cause it to home on a signal (probably acoustic) carrying the messenger to the selected remote suspension point. An alternate solution is a trained seal; a gravity powered glider represents yet another.

An underwater self-powered vehicle is typically rather large, technically sophisticated and expensive. Maintenance and pre-operational checkout will require significant logistic support and spares inventory. Malfunction could result in loss or damage, thus requiring back-up units to avoid jeopardizing the primary mission. The trained marine mammal was not further considered (although the feasibility has been established) due to the specially trained personnel, quartering and subsistence requirements associated therewith.

The concept of using a small underwater glider was evolved on the perceptions that:

- Loss of a single unit would be relatively insignificant in cost
- Many back-up units could be carried at low cost
- Technical/logistic support requirements would be minimal
- In the event the unit malfunctioned, it could be retrieved by the messenger line itself
- A very simple guidance mechanism may be used.

A Rogallo wing was selected for the glider because of its low fabrication cost, as well as the compact storage opportunities which this configuration affords.

The conceptual approach is illustrated in Appendix B, Figure B.1a. The Rogallo wing glider is released under ice at the R/V "Frozen In." It homes on an acoustic beacon set at a depth approximately 1/4 the horizontal distance between the ice-holes. When abreast of the beacon, the glider begins a spiral about the beacon support line, which is rigged with light "grapnel-hooks" to snare a line dispersed by the glider.

With this system the horizontal range is primarily limited by the depth of water available. In principal, the range can be extended indefinitely by advancing from one hole to the next. A powered winch at the remote hole is used to raise the snared glider, and draw the messenger and suspension line to the remote hole.

The suspension line is then reeved onto the remote winch, the remote weight is overboarded by the ship, and the strain assumed by the array and remote suspension line. The remote suspension is hauled to draw the weight and remote end of the array into position. A second weight and suspension are overboarded by the ship and lowered into position, completing the deployment. This scenario assumes that the array has sufficient strength to withstand the tensile loads generated by the above described procedures.

3.3.2 Control of the Array Deployment

The following information must be available to control and execute the deployment:

1. Depth of water
2. Current structure to the depth selected for glider snaring
3. Status (snared — not snared) of the messenger line
4. Submerged depth of both ends of the array
5. Tension applied to the array (both ends)

Item 1 establishes the maximum horizontal range for the (step-wise) deployment of the messenger line, based on the gliding angle of the glider. Item 2 permits a computation of the initial heading of the glider. Item 3 is required to provide positive information regarding the status of the snaring operation. The first two items can be obtained from instrumentation normally available on the ship. Item 3 must be provided as part of the deployment system.

Items 4 and 5 would be incorporated in the array design. The depth information permits leveling of the ends of the array, control of distance below the ice during deployment and avoiding crush depth of array elements, if such limits exist. The tension information provides the data needed to avoid overstressing the system, and monitoring for significant changes of the relative locations of the suspension points or current structure.

3.4 RECOVERY

The obvious procedure for recovery is simply to reverse the deployment procedure from the time after which the suspension line is secured to the remote winch. The information required for recovery is identical to that required for the deployment, excepting information regarding the glider.

3.5 ANALYSIS OF DEPLOYMENT/RECOVERY PROCEDURES

The selection of the messenger technique, with some additional assumptions, permits an analysis of the full cycle of deployment and recovery. For this analysis we shall assume a 10,000 foot (3,048 m) long array having a 3-inch (7.6 cm) diameter and a design current of 0.3 knots (15 cm/sec). We shall also assume that lateral and vertical deflections will be limited to one percent of array length, i.e., 100 feet (30 m). The assumption is that if it is feasible to deploy and retrieve this array, the selected approach will work for any installation for which requirements are not so severe.

3.5.1 Initial Geometry

Other things being equal, the geometry of the suspensions should be selected to minimize the effect of small changes in the separation of the suspension points. This condition is satisfied if $A_0 = \pi/2$; however, in this case, no value of W will impose tension across the array. At the other extreme, i.e., $A_0 = 0$, the tension becomes indefinitely large for any finite value of W. An initial angle of 45 degrees therefore appears to offer a suitable compromise. For this selection, the horizontal component of force, H, equals the weight, W. Given a 1,000 foot (305 meters) array depth, the suspension points must be separated by 12,000 feet (3,658 meters). From earlier work, it has been determined that W must be 16,000 lb (7,256 kg). Recalling the estimate of R, the total reaction due to current, on the array, at each suspension is only 650 lb (295 kg). The angle at the ends of the array, relative to the line connecting the ends, will be less than 3 degrees. With a weight of the size selected, and with A_0 = 45 degrees, the tension in the suspension lines is 22,600 lb (10,260 kg). A factor of safety of 3 is imperative. The breaking strength of the suspensions must thus be 70,000 lb (32,000 kg).

During the deployment and recovery, the remote suspension cable must span the 12,000 foot (3,658 meter) separation. It must be kept between the ice and the bottom. It therefore cannot be buoyant, yet not so heavy as to require a leader of excessive size. A suitable selection for the suspension cable material would appear to be a jacketed KEVLAR. A one-inch (2.54 cm) diameter line of KEVLAR 29 is commercially available; this has an advertised breaking strength of 82,000 lb (37,000 kg). The weight of this cable per unit length in air is 0.389 lb/ft (0.58 kg/m) and in sea water is 0.04 lb/ft (0.06 kg/m).

Now consider the configuration of the suspension line as it spans the 12,000-foot (3,658 meters) distance between the ship and the remote ice hole. If the sag is limited to 2,000 feet (609.6 m), the length cannot exceed 12,800 feet (3,902 meters). Under these conditions, the maximum line tension will be 443 lb (201 kg). The angle of the cable at its ends, relative to the horizontal, will be 35 degrees. If a 0.3 knot (15 cm/s) current flows transversely to the cable, the resistance, R, for the one-inch (2.54 cm) cable will not exceed 0.043 lb/ft (0.064 kg/m). The suspension rope will then stream in a plane inclined 43 degrees to the horizontal, and the maximum tension will be increased to 653 lb (296 kg). The maximum depth of the catenary will diminish to 2,000 ft x sin 43^{o}, or 1,364 feet (416 m).

The strength of the messenger may now be specified at three times the maximum force required to support the remote suspension. This is 2,000 lb (907 kg). A KEVLAR 29 rope with this breaking strength may be had in a 0.16-inch (4.1 mm) diameter. Its weight in water would be 1.02 lb per 1,000 ft (1.52 kg per kilometer).

3.5.2 The Messenger Delivery Problem

As indicated earlier, a Rogallo wing glider was selected for delivery of the messenger to the remote hole. The glider moves forward by virtue of the expenditure of potential energy. Its maximum range is thus a function of water depth, and the ratio of range to depth is given exactly by the vehicle's ratio of lift to drag, L/D. A feasible design, discussed in Appendix B, indicates that an L/D of 4.5 is practically attainable. Thus, for a 2,000 foot (610 meter) assumed minimum depth of water, a horizontal range of 9,000 feet (2,744 meters) may be obtained. There is however a starting transient for the glider, and the acoustic beacon should not be placed on the bottom. Therefore a maximum range of 6,000 feet (1,829 meters) has been selected. For this range a vertical descent of 1,333 feet (406 meters) is required. This will leave some 400 feet (122 meters) of water space above the bottom within which the Hydro-glider could spiral about the capture line. A 12,000 foot (3,658 m) installation would thus require two steps involving a passing of the remote suspension line via an intermediate hole.

The evolutions involved in passage of the messenger are:

a. Launching
b. Guidance
c. Engagement
d. Retrieval

A suggested method for launching is described in Appendix B, and shown schematically in Figure B.2. It primarily involves placing the glider below the ice shield, erecting the vehicle for flight, establishing the initial heading, and releasing the glider. On release, the glider falls until the wing lobes fill and gliding speed (2.9 knots - 1.5 m/s) is reached. The glider then slides down a 12 1/2-degree slope (the glide angle) dispensing the messenger line from a coil (or reel) carried within the payload cab.

No device is built with perfect symmetry. Also, a displacement due to current must be considered. A guidance system is therefore necessary. Three factors must be considered here:

a. Correction for flight path deviations due to asymmetries
b. Correction for flight path deviations due to initial heading errors
c. Correction for flight path deviations due to current.

Items b. and c. are essentially equivalent. Item a. typically requires a one-time adjustment of the steering controls (a calibration). An error-threshold latching-type control system with a central dead band suggests itself as a means to minimize power requirements. The overall approach involves effecting an incremental control deflection to establish a correcting turning rate based on bearing samples relative to the source beacon, taken at discrete intervals of time. The track followed by the glider will thus resemble a classic pursuit-interception trajectory. One critical aspect of the controls problem is a selection of the incremental turning rate and bearing sample interval. These are needed to assure adequate turning rates at the intercept point without developing unstable conditions in the early part of the equilibrium glide flight. A brief study of the kinematics indicate that stable solutions are attainable.

The parawing glider may be steered by either rudder control or by banking (the latter is achieved via a lateral shift in the center of gravity). Selection of the more desirable steering mode is left for the engineering development phase of the Hydro-Glider.

Preliminary calculations of the turning rate which is available with the suggested glider configuration indicate that a turning radius as small as 5 ft (1.5 m) can be attained. The unit will thus enter into a tight spiral after it comes abreast of the beacon. This maneuver will dispose loops of the messenger line about the snaring line. The action of current and settling will thus assure contact between the messenger and the vertical snaring line. To further assure capture of the messenger, the vertical snaring line would be rigged with tripod-like extensions fitted periodically thereto, so that the messenger line will be drawn into the acute angle formed by members of the tripod and the snaring line. These would also serve to prevent the glider from unwinding the messenger from the snaring line, since the glider would tend to be drawn against the projecting structures as the snaring line is retrieved.

The Hydro-Glider, control system, and other elements of the suggested capture system are described in Appendix B.

3.5.3 Effect of Current on the Messenger

The messenger may now be drawn to the surface. It will therefore form a catenary with a horizontal span of 6,000 feet (1,829 meters). The weight in water of the selected messenger will be only 1.02 x 10^{-3} lb/ft (1.66 x 10^{-3} kg/m). The hydrodynamic drag in a 0.3 knot (15 cm/s) crossflow is about 6.84 x 10^{-3} lb/ft (10.2 x 10^{-3}kg/m). The plane of the catenary will be inclined by the current in the manner earlier described for the remote suspension line. The inclination of the messenger catenary will be more severe, however, and could be as much as 80 degrees from the vertical. This poses a significant problem as the messenger could become entangled in the typically extremely rough underside of the ice. To avoid this, in the event of a high velocity current structure, weights will be slid down the messenger prior to a retrieval of the snaring line. A weight of 50- to 100-lb (23- to 45-kg) will suffice to keep the angle of the plane of the catenary between 45 and 65 degrees below the horizontal in the 0.3-knot (15 cm/s) current. The increase in tension in the messenger would be 100 lb (45 kg) at most; this could be easily accommodated by the KEVLAR 29 messenger.

3.5.4 Passing the Remote Suspension and Array

The suspension cable may now be hauled, underwater, to the remote ice-hole by means of a powered winch. As discussed earlier, the length of this rope must be on the order of 13,000 feet (4 kilometers). Depending on the depth of water, sag must be controlled to avoid contact with the bottom. This will require a coordination of scope and tension between the shipboard winch and the remote winch. A cable footage counter and tensiometer, suitable for measuring tension in a running line, should suffice.

The array may now be attached to the ship-end of the suspension rope. An 8-ton tensioning weight is to be attached to the same point. If the weight is passed underwater it will be supported by the suspension and the array. An analysis indicates that the maximum load in the suspension and array will occur at the midpoint of the passage; and, assuming a 2,000-foot (610-m) sag, will reach a value of about 26,000 lb (11,797 kg). Shock loads due to winch characteristics could result in a doubling or tripling of this value. The weight must therefore be buoyed to reduce these loads to tolerable levels; or the weight could be transported over-ice to the remote ice-hole and there attached to the array.* If buoyed, the net suspended weight should not exceed 5,000 lb (2,268 kg). A buoyancy of 11,000 lb (4991 kg) would be necessary. Assuming 50 lb net buoyancy per cu-ft displacement (801 kg/m^3), a sphere 7-1/2 feet (2.3 m) in diameter would be required. This sphere would have to be detached after the array is drawn under the ice and the weight and array lowered back into position. Transport of the weight over ice is obviously preferable.

*The average 3 to 5 meter thickness is more than adequate to support this load when carried on an appropriate sled (see Section 2).

The array will be nominally neutrally buoyant. Some weight must be used to effect depth control during passage to the remote winch site. To minimize the number of items of equipment required, it is suggested that the weight be made up in two units of, say, 2,000 and 14,000 lbs (907 and 6,352 kg) each. The one-ton weight would be attached for the under-ice transfer; and the 7-ton weight would be transported to the remote site and there attached to the array. It should be noted that the 8-ton weights, cast of cubes of iron, will have dimensions of 3.4 feet (1 meter) on a side.

In order for the array to be surfaced at the remote side, the ship-end of the array, the weight and suspension must be in the water. When the remote end is lowered into position, the ship-end suspension will be recovered, in coordination, until the desired configuration is obtained.

3.5.5 Recovery

Recovery is effected by a reversal of the deployment sequence. The remote weight is lifted and the 7-ton unit detached. The ship-end suspension and weight are brought on board. These items are followed by the array, the one-ton weight, and (finally) the remote suspension. Again, coordination of the winches is required, as it was for the deployment.

3.6 TIME REQUIRED FOR OPERATIONS

It is assumed that all equipment is ready and operable, that the ice-holes have been bored and the remote sites established. It is also assumed that the depth of water is known and that a current survey has been taken. The sequence of events are listed along with estimates of time needed to complete the operation. Realistically, the time estimates should be increased by 50 percent to account for communication lag, interpretation of data, etc.

	Event	Launching Assumption	Est. Time in Minutes
1	Lower Glider to Launch Position and Train	-	10
2	Release Glider and Engage Snare	Glider Speed 2.9 knots (5.4 kph) Range 6,000 ft (1,829 m)	30
3	Retrieve Messenger and Glider	Winch Speed 200 FPM (61 mpm)	10
4	Disengage Glider and Messenger, Rig Messenger to Inhaul Winch	-	15
5	Inhaul First Bight of Remote Suspension Rope and Secure	Winch Speed 400 FPM (122 mpm)	20
6	Repeat Steps 1 through 4		65
7	Attach Bitter End of Messenger to Nether End of Suspension Rope and Release		5
8	Inhaul Second Bight of Suspension Rope	Winch Speed 400 FPM (122 mpm)	20
9	Rig Suspension Rope to Winch		10
10	Haul 10,000 ft (3,048 m) of Suspension Rope (i.e., until bitter end of array is reached at the ship)	Winch Speed 400 FPM (122 mpm)	25
11	Attach 8-ton Weight to Array at Junction with Ship-end Suspension and Lower into Water	Winch Speed 400 FPM (122 mpm)	20
12	Inhaul Remaining 2,600 ft (792 m) of Remote Suspension until Nether End of Array Surfaces		10
13	Surface one-ton Weight and Attach 7-ton Weight		20
14	Lower Array into Position	Winch Speed 100 FPM (30.5 mpm)	15
		GRAND TOTAL	275 Minutes (4.6 Hours)

Event	Recovery Assumption	Est. Time in Minutes
1 Inhaul Remote Suspension	Winch Speed 100 FPM (30.5 mpm)	15
2 Detach 7-ton Weight		15
3 Haul Ship-end Array Suspension and Detach 8-ton Weight	Winch Speed 100 FPM (30.5 mpm)	30
4 Haul Array and Detach one-ton Weight	Winch Speed 400 FPM (122 mpm)	35
5 Haul 13,000 ft (3,962 m) Remote Suspension	Winch Speed 400 FPM (122 mpm)	35
	GRAND TOTAL	130 Minutes (2.2 Hours)

3.7 DEVELOPMENT AND TEST

The Hydro-Glider guidance and messenger-line snaring systems represent the only items of moderate developmental risk. The risk here is considered minimal, however, since a slightly more sophisticated guidance system can assure a reasonably high probability of encircling the snaring line. The consequence of this added sophistication is a slightly higher cost for the guidance system. The very small turning diameter which the glider is capable of attaining (less than 10 feet, 3 m) assures an ability to spiral about the snaring line.

The remainder of the development effort is straightforward. The Arctic environment must be recognized in specifying machinery, materials, etc. A significant technological base exists in this area, however, hence no significant technical risk is foreseen.

Two aspects of the environment must be given special consideration. These are the effect of low temperatures on storage battery capacity and the handling of wet cable in the Arctic environment. In the latter case, selection of water-blocked and jacketed cable (or rope) would avoid the problem of freezing, in place, on the winch drum after immersion.

The array itself must be treated as part of the system, and provision made to install depth sensors at both ends, rather than at the front end, as is usual for most towed applications. Also, the tension information should be relayed through the array to the ship. This will require additional channels in the array data transmission system. An array with a central strength member is indicated in order to sustain the very large tensile loads required in meeting the configuration limitations imposed in this study.

The geometry of the attachments for the suspension line and the array must be carefully considered with respect to deployment and retrieval geometry as well as the torsional characteristics of the suspension line itself. Shackles, pins, etc. used for connecting members should be designed to avoid rattling or clanking.

The winch and handling machinery, at the remote site, would preferably be integrated on a single platform to take advantage of a common power source. An alternative would consist of using a diesel-electric drive for a D.C. powered winch and crane. This is attractive in the Arctic since D.C. power provides for good control chrateristics without the drawbacks associated with hydraulic and direct mechanical drives.

The development of procedures, supported by algorithms that permit definition of system status from easily measured data, is necessary to make available the information needed to exercise intelligent control over the operation. The ship's computer could be used for this purpose. Otherwise, the computational capacity represented by the currently available generation of portable computers will easily suffice.

Testing the mechanical and procedural aspects of the proposed system is necessary. At least some of the personnel involved in an actual under-ice emplacement should participate in such a testing program. Almost all of the mechanical elements can be tested independently, e.g, winches, ropes, cranes, etc. The cost of a full-scale test could be considerable. The following system developmental tests are therefore suggested in lieu of a full-scale field exercise:

a. Full-scale testing of the messenger delivery system.
b. Scale model testing of a system installation to prove (and familiarize personnel) with procedures, use of data for control purposes, communications and simulated malfunctions of various elements.

The tests suggested in b, above, in order to be meaningful, should most probably be exercised in at least 1/4 scale. For 1/4-scale models, weights of components and forces would be decreased by a factor of 64. Hence equipments of ordinary capacity and size could be utilized in an efficient and effective manner.

The full-scale tests of the messenger delivery system should be exercised in an area of the ocean in which a definable current structure exists. An oceanic region with approximately 2,000 foot (610 m) depth and a reasonably well defined current structure is required.

3.8 SUMMARY OF APPROACHES CONSIDERED

Two major approaches for inserting the array under the ice were given consideration. These included the deployment through holes, and the insertion through a slit, or trench made in the ice.

The trench method would consist of laying the array in the manner of a pipe line, as illustrated by Figure 3.2. This method would permit the array to be inserted at minimum tension, since it could be unreeled under very low tensile loads. This method was rejected because:

a. Machines such as the one illustrated in Figure 3.2 could not traverse ice ridges,
b. The depth of trenching is limited, and
c. Since the trench would re-freeze, a second trenching would be required for recovery; or the array would have to be recovered under-ice by means of winching.

Thermal and chemical means for trenching were rejected on the basis that the first would require excessive energy and be difficult to apply, while the second is believed to be untried.

The deployment method of insertion therefore emerges as the one preferred. Here two approaches were considered for the insertion:

1. Directing the end of the array toward the desired location by means of dynamic thrust (this approach offers the possibility that the array could be maintained in position by the same means).

To study the feasibility of using the ice as a platform from which to lay or pull pipe across the bottom of ice-covered channels, Polar Gas used a conventional land pipeline ditcher, capable of trenching through up to 15 feet of ice. (Polar Gas Photo, 1973.)

Figure 3.2. Illustration Taken from Marine Technology Society Journal, December 1975, p. 26

2. Passing a leader or messenger to the desired location (a second hole through the ice) and then hauling over a larger cable, which in turn is used to haul the array into position.

The first approach, above, was rejected because:

a. The array (by virtue of its nominal neutral buoyancy) would require weighting to assure that it does not come in contact with the underside of the ice. The weights would have to be dropped (say by corroding links) so that the array could assume its horizontal position. Electrical breakouts, in the array, would be required if the weights were to be dropped on command. This would unduly complicated the system.

b. The power needed to develop the required thrust in supporting the array, in a moderate current, would be excessive. The 8-ton tensile load required for the 10,000 foot (3,049 m) long array would necessitate prohibitively large components. A high technological risk would be involved, and the noise field generated by such equipment would be counter-productive.

c. The Thruster would require extensive logistic and technological support. Reliability of this scheme would be questionable.

The use of a messenger is therefore indicated.

The problem has now been narrowed to the selection of a method for passing a messenger below the ice. The considerations underlying the selection of a Rogallo-wing type glider have been discussed in Section 3.3.1.

3.9 SYSTEM PERFORMANCE TRADE-OFFS

In Appendix A it is shown that for nearly neutrally buoyant arrays the important deflections are contributed by the current. It is shown also that the effect of current on the maximum horizontal deflection of the array, relative to its ends, for a current flowing normal to the length of the array is very accurately given by the equation for the parabola;

$$z_1 = RS/8H_o. \qquad (3.6)$$

Here z_1 is the ratio of the maximum lateral deflection to the length, S is the total length and H_o is the horizontal component of tension. Recall that the tensioning weight is given by Equation (3.1). Solving Equation (3.6) for H_o,

$$H_o = RS/8z_1$$

or,

$$H_o \sim V^2S/z_1,$$

where V is the speed of the current. To illustrate the trade-offs available, the parameters associated with various combinations of length, current speed and deflection ratio are shown in Table 3.1

TABLE 3.1

z_1	V/Kts	S/Ft	H_o/lb
.01	.3	10,000	16,250
.1	.3	10,000	1,625
.01	.2	10,000	7.222
.01	.1	10,000	1,805
.1	.1	10,000	181
.01	.3	1,000	1,625
.1	.3	1,000	163
.1	.1	1,000	18
.01	.3	100	162
.1	.3	100	18
.1	.1	100	2

These results are accurate to within about 10% for values of $z_1 \lesssim 0.1$

A wide latitude of design possibilities therefore exists. In particular, the magnitude of the weight may be substantially reduced if a smaller value of the design current is deemed acceptable.

Section 4

SEISMOMETER IMPLANTMENT/RETRIEVAL

4.1 BASIC CONSIDERATIONS

Seismic measurements on the ocean floor are being successfully performed today. A commonly used technique is to free-fall a self-contained seismometer package (power supply, recording equipment, etc.) to the ocean floor where the data are recorded. For recovery, an acoustic release discharges ballast and the slightly buoyant seismometer package floats to the surface where it is recovered. This method of recovery is precluded for measurements taken under an ice shield, however, as the slowly drifting ice carries the access hole away from over the seismometer.

In considering basic concepts by which the seismic measurements might be made under-ice, one should ask:

1. Can the seismometer be considered a disposable item?
2. Can the data be reliably obtained without either recovering the seismometer or by use of a cable?

For the present case, answers to these questions are judged to be "no" in both instances. Consequently, the conceptual configuration of a seismometer experiment under ice is restricted to the case of a seismometer on the bottom connected to a ship locked in ice, via an electromechanical cable. The problem then becomes one of a proper configuration to permit successful deployment, operation and recovery of the system.

The configuration should assure that the ship-to-package cable does not transmit any forces, especially dynamic forces, to the instrument package. It is assumed that once the seismometer has been put in place on the bottom, the ship will drift with the ice pack, deploying cable until its limiting length is reached and the seismometer must be retrieved. It is anticipated that relatively long measurement times are desired. Indications are that drift rates of polar ice will be on the order of one to two miles per day. The bottom type is largely unknown, but a mud bottom is judged to exist over most of the area. Bathymetry data shows bottom slopes to be gentle or flat in most areas with depths of about 12,000 feet (3,658 m) in the deep plain areas. Currents are not well known either, but there are indications that "surface" currents are of the order of 0.1 knot (5 cm/s) and less.

Given that the above represent baseline operational and environmental conditions, then the identification of potential design configurations rests on satisfying the major problem areas which are perceived. The lowering, by cable, of an instrument package to rest on the ocean floor, from a surface ship, is not considered to be a difficult problem provided currents are not high, ship accelerations are not excessive, and that the instrument package can sustain landing shocks. For a ship locked in ice, in deep water, this is not a difficult scenario provided an open hole through the ice can be maintained. Once on the bottom, however, two problems become apparent as the ship drifts, in ice, away from the instrument package position.

1. Providing a cable configuration which does not result in interference with the seismic measurements; and,
2. Retrieval of the package.

Retrieval of the package must be discussed first since the method by which this is to be accomplished bears on the cable configuration and its potential for interference with seismic measurements. If the package were to be retrieved simply by winching in on the cable then the cable and package must be capable of being dragged some distance along the bottom. As a consequence it is desirable that there be a high probability of them not snagging on an outcropping or underwater obstacle. Our uncertain knowledge of the bottom topography could not support this high probability judgement. On the other hand, floating the package to the surface (i.e., to the subsurface of the ice pack), for retrieval, is precluded by the ice cover which has a "rocky terrain" for its lower surface. The retrieval operation would seem to require that the cable and instrument package have minimum contact with both the bottom and the "surface" during retrieval.

The problem of insuring that the cable does not interfere with seismic measurements requires that it be isolated either from the package or the dynamics of the environment. The latter could be approached for example, by laying excess cable on the bottom. But a long length of cable on the bottom has already been identified as a threat to successful retrieval. It is judged, therefore, that instrument package isolation is a major design consideration.

4.2 CONFIGURATION CONCEPT

The configuration of the cable between the ship and the instrument package is important to package isolation and retrieval. In addition, a proper configuration must be maintained, as the ship drifts, to prevent excessive line tension or dragging of the package. Excessive payout of cable, however, could jeopardize recovery by subsequent tensioning of excess cable loops. Certain features of the cable configuration appear desirable:

1. It should be configured off of the bottom.
2. The outboard end should be terminated in an anchor so that current forces or any cable dynamics would be isolated from the seismometer package.

The major elements in the overall configuration are shown in Figure 4.1.

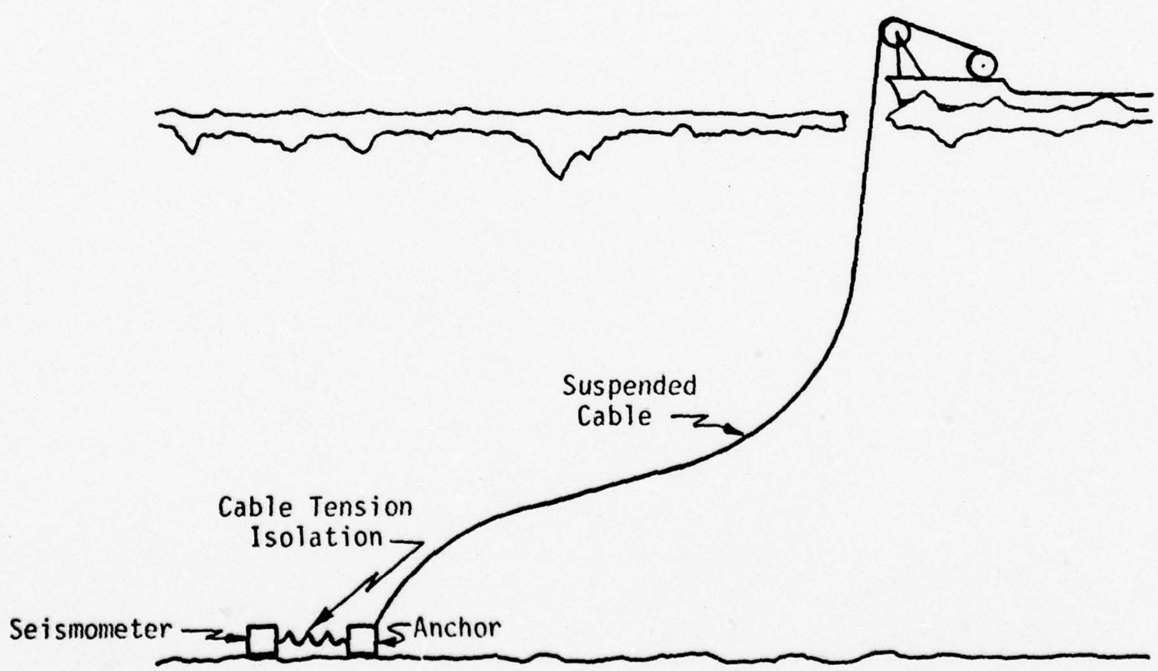

Figure 4.1 Major Elements in the Installation of a Seismometer Under Ice

How suspension is provided to the cable is a question with operational implications. Since it is undesirable to drag the seismometer package along the bottom during retrieval, some mechanism for making the seismometer buoyant, at retrieval, is indicated. If the whole system becomes buoyant at retrieval, however, it will ultimately be dragged along the rough lower surface of the ice pack, which is also undesirable. A cable configuration is proposed whereby only the key elements are made buoyant at retrieval; however, the total system remains "heavy" as shown schematically in Figure 4.2.

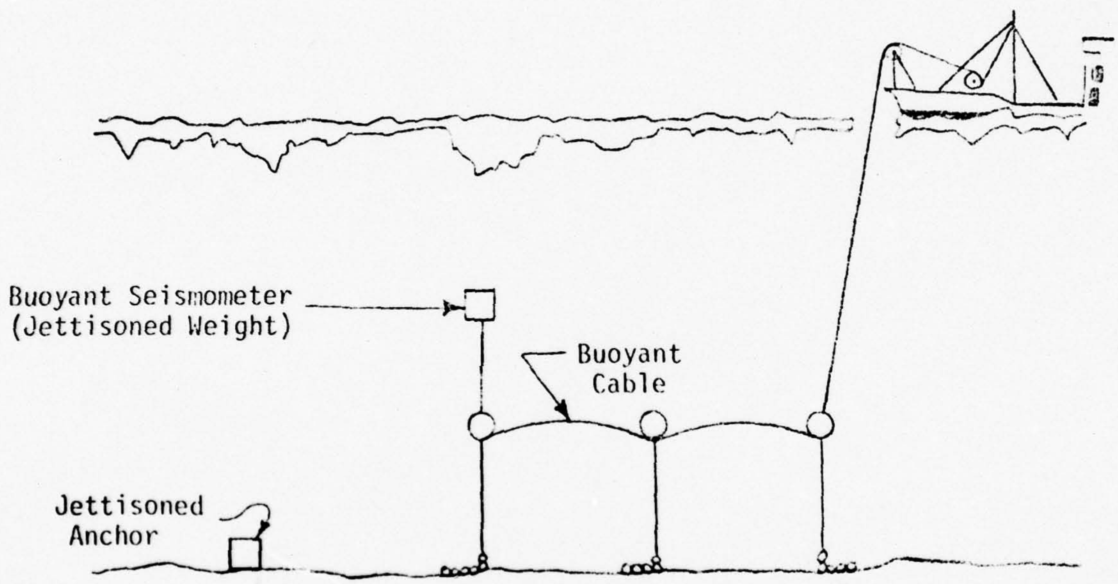

Figure 4.2 Schematic of Arctic Seismometer System in Retrieval Configuration

This system envisages a slightly buoyant cable which is also buoyed at discrete points along its span. Each buoy is considered to have some excess buoyancy over that required to support a riser. Beneath each buoy is a riser which terminates, at the lower end, in a length of small sized chain. The natural configuration of the riser will place the buoy within a small height band above the bottom, one in which enough chain has been layed on the bottom to produce a force balance in the vertical direction. In preparation for retrieval, weight is jettisoned from the seismometer package making it buoyant; the anchor is jettisoned, and the system is retrieved by inhauling cable and detaching the buoys (possibly the risers also) as they come to the surface. The buoyancy in the seismometer package may have to be jettisoned to permit its retrieval through the ice hole.

4.3 INSTALLATION

The installation sequence is envisioned as shown in Figure 4.3. Installation of this system is somewhat different from the usual installation problem from a ship at sea. For installation from a ship locked in ice, two obvious differences are apparent:

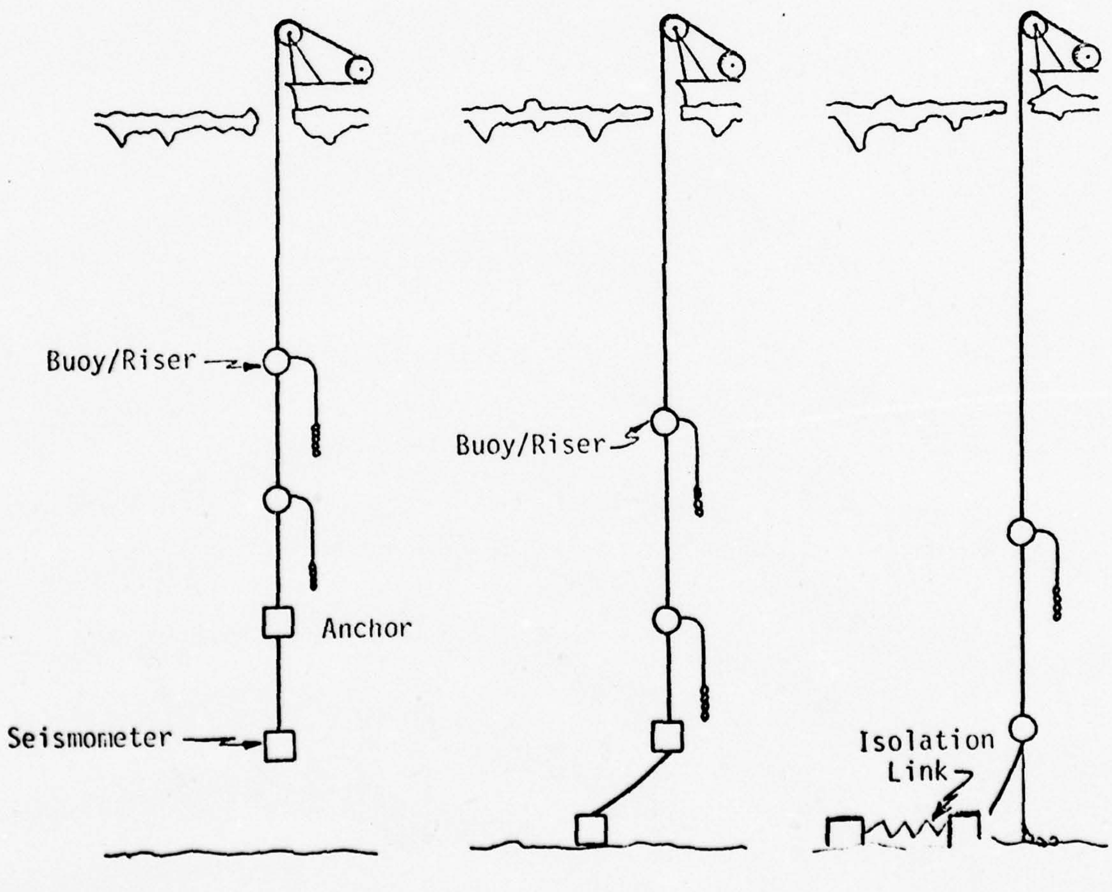

Figure 4.3 Installation Sequence

1. The ship has no maneuverability

2. There is no ship acceleration (in response to seas)

This second condition is advantageous in placing a delicate instrument package on the bottom. The first condition, however, indicates a problem in the initial streaming of the cable. Once the seismometer has touched bottom, it would be desirable to bottom the anchor quickly and to develop sufficient line slack to insure that any subsequent dynamics, transmitted by cable, do not disturb the seismometer package. For the normal at-sea installation this is accomplished by determining the ship's drift rate and deploying cable at a slightly greater rate. For a ship locked in ice, the drift rate is very small, and so are the dynamics due to wave forces. Dynamics due to varying currents, however, should be expected--thus an immediate grounding of the anchor, and the development of excess slack would be useful. Without measurable ship drift, however, there is the danger of deploying the anchor on top of the seismometer; and, the added danger that excess cable may be "dumped," in quantity, on the seismometer. These conditions would ultimately interfere with recovery. To allow the anchor to be grounded immediately, without the danger of its being dumped on the seismometer, a pivoted stiffening member could be used to link (and separate) the two modules during the installation phase. This is schematically shown in Figure 4.4.

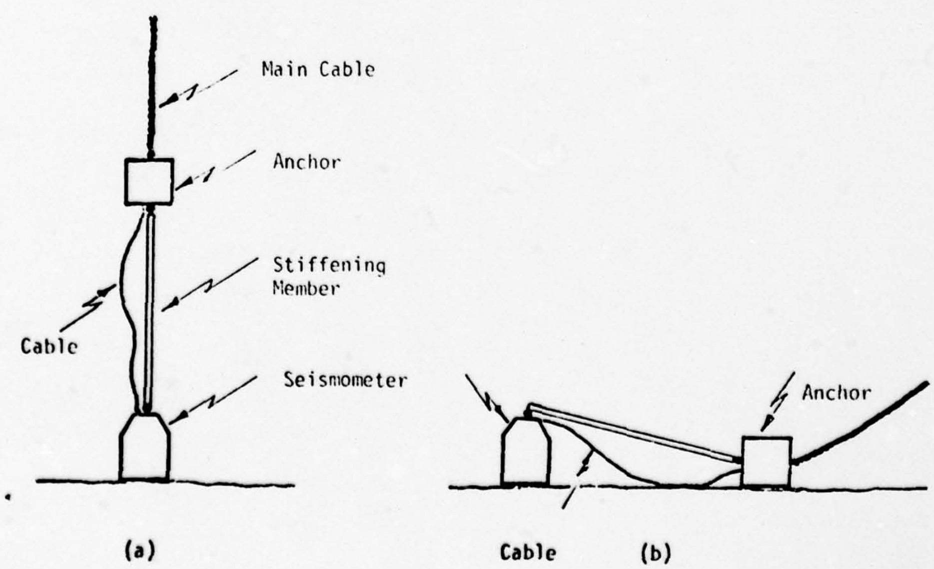

Figure 4.4 Scheme for Preventing the Lowering of the Anchor onto the Instrument

After the anchor is down the stiffening member link is broken (e.g., by explosive pins or an acoustic release). The only link, then, between the anchor and the seismometer is the slack cable spooled in the seismometer package. This cable pays out as the anchor is moved to its set point under tension applied through the main cable, but it must retain its slack state to prevent dynamic forces from being transmitted to the seismometer during measurement periods.

4.4 CABLE DEPLOYMENT

The ship locked in ice should be expected to drift at a slow rate and in uncertain directions. Figure 2.4 shows historical data on ship drifts. Figure 4.5 shows the erratic drift of Fletcher Ice Island over a period of about three years. These paths are seen to frequently loop back. Cable must be deployed to match the drift of the ship after the seismometer has touched bottom, and until the unit is recovered. To assist this operation the ship must continually monitor water depth and ship position relative to the anchor. In this regard these relative positions could be measured acoustically with pingers. Cable scope must then be modified to maintain the desired configuration. The desired configuration involves a steep cable angle at the ship, with low horizontal cable tensions developed in the lower part of the cable.

It is undesirable (from the standpoint of system recovery) to overlay cable. It is necessary, therefore, to maintain a continuous record of ship position relative to the seismometer, and to keep an accounting of the amount of cable in the water. There is a small but finite danger that once the seismometer and anchor are on the bottom, the ship may drift in a direction so as to pull the anchor back over the seismometer. Should this situation be detected the system should be retrieved and redeployed.

4.5 ANCHOR

Even though indicated ship drift rates are small, and there are essentially no surface waves to creat ship accelerations, the cable must be isolated from the seismometer. This is a requirement since it must be considered that the system is acted on by steady-state and transient currents. In addition there is, generally, a horizontal component of tension present in any line suspended between two points and this component must be resisted at the outboard end of the configuration. Thus the need to anchor the cable is apparent. The anchor must

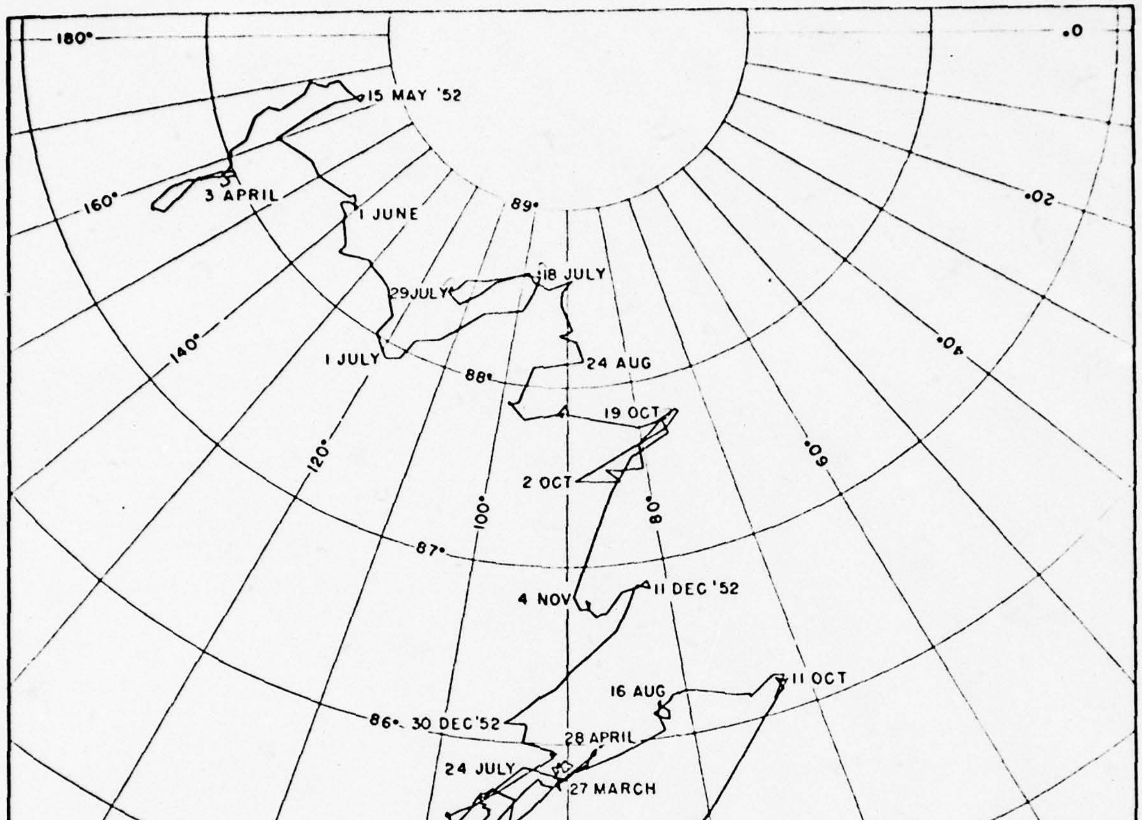

Figure 4.5 The Drift of Fletcher Ice Island
"Arctic Sea Ice," National Academy of Sciences, Publication 598, p. 192.

be located inboard of the seismometer to isolate the instrument from cable dynamics. This anchoring scheme requires that the anchor be deployed near the seismometer as illustrated in Figure 4.1.

The anchor may be in the form of a clump, or it could be shaped if a higher holding-power-to-weight ratio is needed. Regardless of which type is used, however, the anchor will necessarily tend to travel in the direction of any applied force. Hence the system used for anchor-to-seismometer isolation must account for any expected anchor travel.

The travel distance will be directly related to the time under load and to the level of applied force. Items to be considered in the selection of anchor type are:

a. Clump anchors typically have low holding-power-to-weight capabilities. For this application, at retrieval of the system, the clump anchor must either be jettisoned, dragged across the bottom or made buoyant. If the installation is to be reestablished frequently, over an extended period of time (e.g., years), then jettisoning could be prohibitive in terms of cost and logistics.
b. Shaped anchors, such as fluke type anchors, or mushroom anchors, must travel across the bottom to "set." The travel distance will depend on bottom type and is difficult to predict. Anchor design should however be matched to bottom type. For example, mushroom anchors are effective in mud but are not effective in hard sand. Conversely, LWT type anchors with 30° fluke angles are effective in hard sand but not in mud. At retrieval a well set anchor may not be broken out without extraordinary cable force being applied at a shallow angle (the ship has presumably drifted several miles away from the anchor).

As an estimate of the anchor force required during operation, consider a typical configuration in a current. Assuming lengths on the order of 50,000 feet (15,240 m) of 0.75 inch (1.9 cm) diameter cable are to be suspended in a 0.2 knot uniform current, normal to the "plane" of the configuration, and a drag coefficient of 1.2, a total force of 428 lbs (194 kg) would be acting on the system. As a first approximation it can be assumed that one-half of this force is resisted at the ship, and the other half at the anchor. Thus the anchor would be required to absorb approximately 214 lbs (97 kg) of force. A clump weight of 428 lbs (194 kg) would be indicated for a holding power-to-weight ratio of 0.5.

Shaped anchors, on the other hand, have higher holding power. For the more common types, such as LWT, Stockless, mushroom, Eels, etc., there are data on the larger sizes which weigh from 1000 to 5000 lbs (454 to 2,269 kg). These anchors have holding power-to-weight ratios of from 3:1 to 6:1 for mud bottoms. The smaller Stato anchors are reported to have developed holding power-to-weight ratios as high as 15 to 1 in mud. In general, the holding power-to-weight ratio becomes higher as the anchor becomes smaller.

4.6 CABLE

The cable could be buoyant, neutral or heavy in water. The weight of a cable has implications at launch and retrieval, but most importantly for the inplace configuration. The desirability of a cable supported off the bottom has been indicated. If the cable is heavy in water, discrete buoyancy modules, located at spaced intervals, are required. A heavy cable is desirable because it connotes a small diameter cable and results in more efficient storage aboard ship. There is a problem, however, in supporting a heavy cable off of the bottom unless the support points are rather close together. As an example: a cable weighing 0.05 lb/ft (0.07 kg/m) in water could be supported by 2 foot (0.61 m) diameter spherical floats (γ = 0.5) located every 2,500 feet (762 m) along the cable. This would provide a slight surplus of buoyancy to support the riser leg. However, for a cable of this weight, with buoys at 2,500 foot (762 m) intervals, significant tension would have to be maintained therein to keep it from sagging to the bottom. For example, if a horizontal force (H) of 100 lbs (45 kg) is maintained, the support buoys would have to be more than 360 feet (110 m) above the bottom; if H is 200 lbs (90 kg), buoy height must be almost 200 feet (61 m). This means long riser legs and an increased danger of riser leg entanglement with the cable, during deployment. It also means that cable tension must be maintained within narrow limits throughout the system; enough to keep the cable off the ground but not so much as to overload the anchor and cause excessive anchor travel. Relieving this cable sag problem would require either a reduction in buoyant riser separation distance (which complicates deployment/retrieval/storage), or reducing cable weight, or both.

Neutral buoyancy is virtually impossible to attain in the general case. A slightly buoyant cable would have the advantage of eliminating the suspended cable sag problem--thus allowing the riser buoys to ride only a short distance above the bottom, and keeping riser leg lengths to a minimum. The riser buoy separation distances along the cable could then be rather large, yet close enough together to "control" the cable in a current. The use of a high strength, buoyant cable is therefore indicated.

An electromechanical cable seems feasible, with KEVLAR as the strength member and sufficient buoyant material (e.g., thermoplastic rubber) to support the weight of the KEVLAR, the electrical core, and to provide an excess of buoyancy.

4.7 SEISMOMETER-TO-ANCHOR ISOLATION

Once the seismometer package has reached the bottom it should be isolated as quickly as possible from the remainder of the system. Isolation implies that the anchor is in place and functioning against any cable loads. A method for isolating the seismometer is by acquiring sufficient slack in the line between the anchor and the seismometer. It is not apparent that this can be accomplished on a one time basis. Rather, since it must be assumed that the anchor will continue to travel under applied load, some provision must be made to insure that isolation is maintained throughout the seismic measurement period. A slack cable link between anchor and the seismometer would seem to be necessary and sufficient. A sufficient length of excess cable would need to be stored in the anchor or seismometer package (probably the latter) to be payed out as required by anchor travel. The link would be configured so that it does not support tension in the line when the two packages are on the ground. During the lowering phase, however, even though there is a stiffening member between the anchor and seismometer, the cable link will have to be constrained in scope. After touchdown of the anchor and jettisoning of the stiffening member, the free deployment mode of the isolation cable will be activated.

4.8 CABLE CONTROL RISER

The need for this device has been discussed previously. Although the cable is buoyant, its configuration should be "controlled" near the bottom. The riser configuration shown in Figure 4.6 provides for these basic requirements. The buoyancy of the buoy, and that of an added span of cable, should be enough to support the riser and some small amount of chain. (If the cable could be made sufficiently buoyant, then a buoy would not be necessary.) The question of where to put the buoyancy must be addressed in design trade-offs, with implications having to do with cable storage, cable manufacture, and the handling of the riser assembly during deployment and retrieval. At retrieval the chain

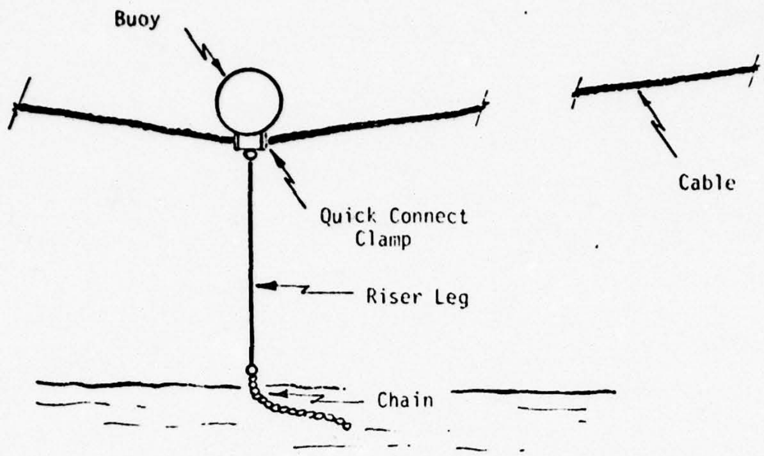

Figure 4.6 Schematic of Cable-Support System

portion of the riser must drag the bottom; thus it may become entangled with an obstacle. A weak link in the riser would assure breakaway. The riser leg itself should be a stiffened member for that portion nearest to the main cable. During deployment this stiffened member would assure a standoff of the chain and thereby prevent entanglement, as illustrated in Figure 4.7.

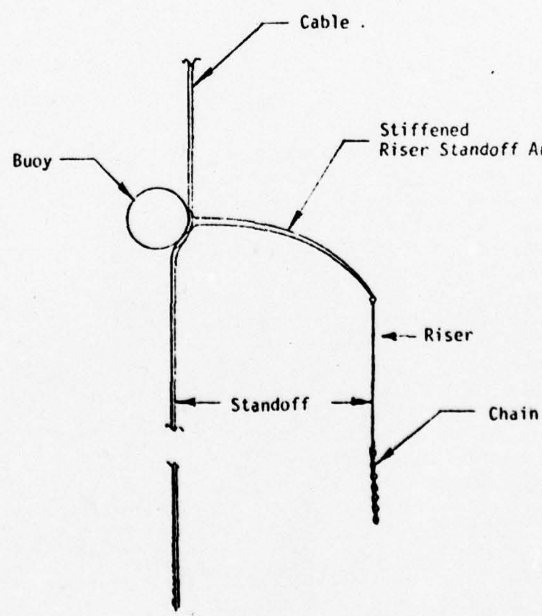

Figure 4.7 Riser Configured for Lowering

4.9 RECOVERY

Recovery of the system is initiated by jettisoning both the seismometer ballast and the anchor; see Figure 4.8.

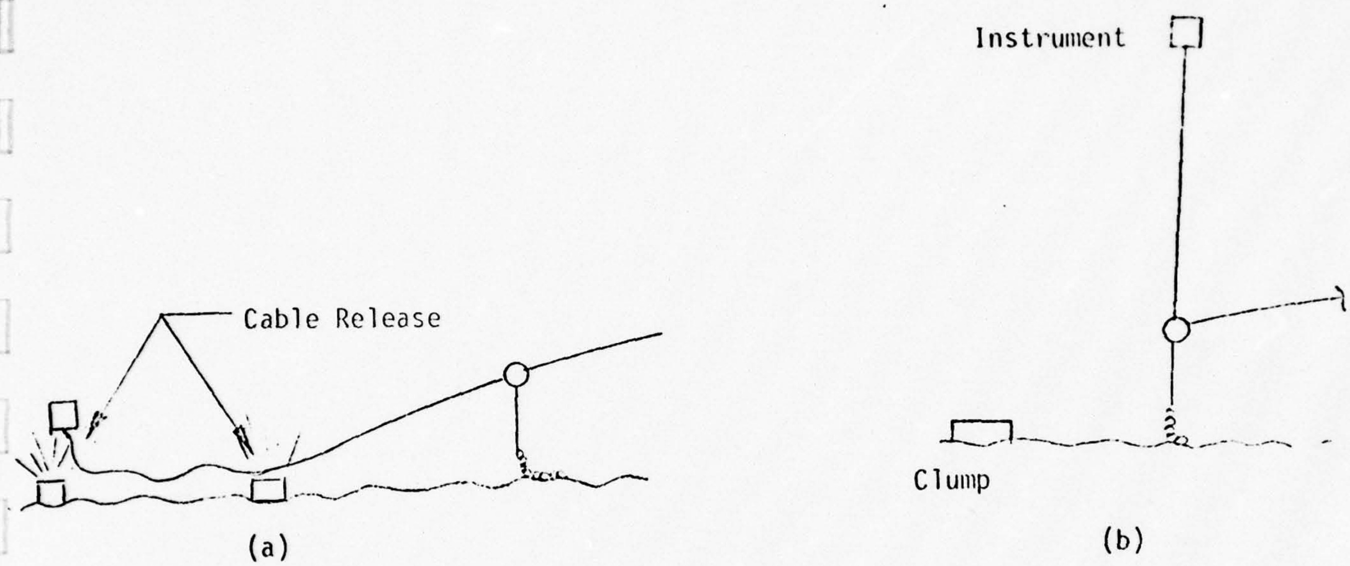

Figure 4.8 Initial Recovery Sequence

This can be accomplished by means of a signal from the ship, through the cable, to the release mechanisms. This would require an electrical takeout at the anchor (or an inductive coupling, if cable design permitted). The seismometer package could then rise to a height on the order of hundreds of feet above the bottom. At this point the ship winch inhauls on the main cable causing the cable "suspension" risers to drag along the bottom. It is at this point that the weight of chain in the riser legs comes into play. Tension, applied to the cable to drag the system across the bottom, will tend to shallow the cable angle at the ship; this is particularly true for a buoyant cable. This raises the danger of abraiding the cable on the edge of the ice hole. It is desired, therefore, to keep a steep (nearly vertical) cable angle at the ship. By a proper selection of weights in the riser legs the angle of the cable at the ship can be kept steep while a horizontal tension is applied at the bottom to cause the system to drag. The resistance here is that due to friction between the chain and the bottom (about 0.5 w in mud). If a chain leg should snag on the bottom, a weak link must be provided in the riser so that the remainder of the system can be freed for inhaul. As riser legs are inhauled through the ice hole, those portions not suitable for storage on a reel are removed. When the last (outboard) riser leg has just reached a position below the ship the configuration will appear as in Figure 4.9.

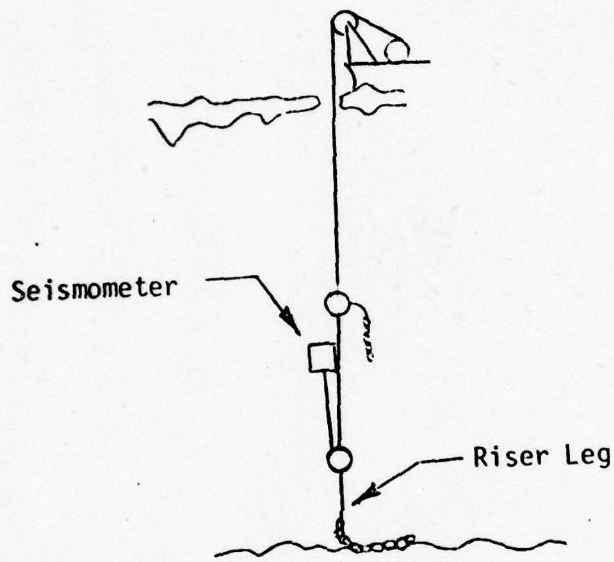

Figure 4.9 Final Stage of Recovery

At this point a danger exists of entangling the seismometer with the main cable. Light currents would tend to stand the seismometer off and prevent tangling but this action is not certain. In addition, as the final part of the system is inhauled and the buoyant seismometer package nears the surface, if the seismometer cable has not wrapped around the main cable, it should not be expected to surface through the ice hole unless a rather large opening can be maintained. Therefore, as the final part of the cable system nears the surface, the seismometer should be made slightly heavy, again, by flooding or jettisoning buoyancy and allowing the system to become a "single vertical line" configuration for recovery. Care will have to be exercised in the design to insure that the seismometer sink rate, when flooded, is not high enough to create high cable snap loads as the seismometer descent is terminated. The possibility of entanglement exists in all phases of this final stage in the recovery. However, the cable tensions are rather low at this stage and permanent damage to the cable in such an event is not likely. If damage does occur, cable can be cut and removed prior to a subsequent installation. A few hundred feet should be affected, at most.

4.10 HOUSEKEEPING INSTRUMENTATION

To insure a successful operation it will be necessary to have certain measurements taken during the deployment and the retrieval phases. These are noted below:

<u>During Deployment</u>

1. Seismometer height off the bottom as it approaches the bottom (measurement by sonar)
2. Seismometer orientation at touchdown and after settling
3. Cable tension at the ship and at the anchor
4. Cable scope out

<u>During Operations</u>

1. Tension in the link between the anchor and the seismometer
2. Ship coordinates and seismometer package coordinates (or their relative positions)
3. Seismometer orientation
4. Cable tension, at the ship and at the anchor
5. Cable scope out

<u>During Retrieval</u>

1. Actuation to effect a release of ballast at the seismometer and anchor will be required. An instrumentation signal to confirm the actuation will be required.
2. Tension in the cable
3. Depth of the seismometer or height off the bottom
4. Cable scope

4.11 DEVELOPMENT AND TEST

All of the technology required for the proposed system is state-of-the-art. A considerable test and evaluation program for the operational procedures will be required. This is needed to be assured of component reliability, especially in the retrieval phase. The performance of the proposed anchor, in the expected bottom types, must be established; also the characteristics of chain trenching across these various bottom types is needed.

4.12 SUMMARY OF OTHER APPROACHES CONSIDERED

As mentioned earlier, the simplest approach to setting a seismometer on the ocean floor under the Arctic ice is to treat the unit as being disposable. Information could be digitized, buffered and thence transmitted acoustically. Another unit would be launched when the ship drifts out of the acoustic range of the device. Long range acoustic transmission requires high power output. Low power requirements imply the use of many devices. Malfunction results in loss of data and requires launching a second device. These broad considerations appear to provide sufficient reason to drop further consideration of this approach, in view of the perceived cost and development that would be required. Retrieval of the instrument is therefore judged to be necessary.

The concept of an independent seismometer with an acoustic link could be approached on the basis of using a powered, controllable vehicle to retrieve the unit. A submersible such as ALVIN would be a suitable vehicle if the range within which retrieval is accomplished is suitably limited and high currents are not expected to be encountered. The necessity for a light submersible to return to the entry hole would pose an unacceptable risk, in our opinion, if the submersible traveled more than about a thousand meters (3,280 feet) from the ice hole. The range limitation would imply very frequent use. Also, the submersibles may require modification of life-support and control systems for Arctic use. Special support gear would be required, as would extensive technological and logistic support. The concept, though not infeasible, was discarded on the basis of these considerations.

An extension of the above concept would embody the seismometer in a mobile, self-powered vehicle that would, as the ship drifted to the edge of the acoustic transmission range, rise above the bottom and navigate toward a beacon lowered by the ship. The concept is technologically feasible. The development cost, technological and logistic support, and risk of loss in the event of malfunction are judged unacceptably high in comparison with other approaches.

If the seismometer is connected to the ship via a cable, it may be launched, monitored, and retrieved thereby. Several possible approaches are identified. The concept of laying the connecting cable slack on the ocean floor was discussed in the earlier matter, as was the use of a light or neutrally buoyant cable. The use of a heavy (in water) cable without supports was also examined. A configuration unencumbered with buoys and other appurtenances offers a substantial advantage with respect to winching and on-reel storage. The necessity for an anchor between the instrument and cable has been established. If the cable is not to lay on the ocean floor, its suspension is maintained by a proper control of scope, and thereby cable tension could become extremely large. If the instrument is to remain on station for any significant time, several miles of cable will be required. An installation in water of moderate depth (say 1,000 feet, 305 m) would require a tension in excess of that reasonably supportable by either the cable or the anchor. Also, when the anchor is jettisoned for recovery, as would be necessary if it is large, the entire system would be subject to an impulsive "jerk" toward the ship, and a great length of the cable would settle to the bottom. This constitutes an unacceptable risk.

The concept developed in the preceeding sections was therefore adopted.

Appendix A

PERFORMANCE PARAMETERS FOR A SUSPENDED STATIONARY ARRAY

A.1 GENERAL

The relative positions of the hydrophones within an array must be maintained within certain tolerances in order to achieve a given level of acoustic performance with respect to gain, beam forming and beam steering. The detailed investigation of these acoustical factors is quite complex and exceeds the scope of this study. Nevertheless, it is this consideration that establishes the physical characteristics of the support structure.

Not having a specific array to consider, generalized requirements must be developed. The major factors that determine the shape of an array are:

1. Distribution of weight along the array (assuming uniform diameter over the entire array),
2. The current and its orientation relative to the array, and
3. The horizontal component of tension in the support cables.

A.2 EFFECT OF WEIGHT

Array fabricators apparently are capable of ballasting arrays to within ±1% of the displaced volume of sea water of given density. The expected maximum variation from neutral buoyancy (NB) should thus not exceed 1% of the displacement volume. The sag of an array <u>in situ</u> will not then exceed that computed on the basis of the maximum ballasting tolerance.

The computed configuration will be that of a catenary, for which the relation between the sag, $\overline{Y}$, length, S, horizontal component of the applied tension, H_0, and weight per unit length, w, is

$$\frac{\overline{Y}}{a} = \sqrt{1 + \left(\frac{S}{2a}\right)^2} - 1, \qquad \text{(A.1)}$$

where $a = H_0/w$. Then

$$a = \frac{(S/2)^2 - \overline{Y}^2}{2\overline{Y}} .$$

Setting $$\bar{Y} = KS,$$

$$\frac{H_o}{wS} = \frac{0.25 - k^2}{2k}. \qquad (A.2)$$

Assuming a departure from N.B. of one percent of the displacement,

$$H_o/S = 0.0035\ (0.125k^{-1} - 0.5k)\ d^2 \qquad (A.3)$$

where S is in feet and d is in inches.

To obtain a preliminary feel for the weight required to limit the sag, note that for $k = 0.01$ and $d = 3$ inches, $H_o/S = 4 \times 10^{-1}$. The weight required, for $A_o = 45^o$, is then about 4,000 lb per 10,000 feet.

A.3 EFFECT OF CURRENT ON ARRAY DEFLECTION

A.3.1 Relative Importance of Current and Weight

The unit hydrodynamic loading is given by

$$R = C_R(\rho/2)V^2\, d$$

and the departure from N.B. by

$$w = 0.01\ \rho g\ \frac{\pi d^2}{4}.$$

The ratio is

$$\frac{w}{R} = \frac{5 \times 10^{-3}\ g\ \pi\ d}{C_R V^2}.$$

For $C_R = 2$ and $V = 0.3$ knots (15 cm/s), the numerical value is

$$\frac{w}{R} = 0.985\ (\text{ft})^{-1}\ d$$

$$= 0.082\ (\text{in.})^{-1}\ d.$$

That is, for arrays less than 12 inches (31 cm) in diameter, the hydrodynamic resistance is the important factor in controlling deflection.

A.3.2 Equilibrium Configuration of an Array Suspended in a Current

A neutrally buoyant array is suspended from the ends in a current. If ϕ is the angle in between a normal to the array and the current, the curvature is

$$\frac{d\phi}{ds} = \frac{R}{H_0} \cos^3 \phi. \tag{A.4}$$

Taking the point of maximum deflection as the origin, and defining $\phi = 0$ at that point, the array will be symmetric with respect to the midpoint. Integrating Equation (A.4),

$$\frac{1}{2}\frac{\tan\phi}{\cos\phi} + \frac{1}{2}\tanh^{-1}\phi = \frac{Rs}{H_0}, \tag{A.5}$$

where the initial conditions $s = 0$, $\phi = 0$ have been applied. The maximum angle occurs at the ends of the array, under the condition that $s = S/2$. Denoting $\phi\ (S/2)$ as ϕ_1, and $RS/2H_0$ as α, Equation (A.5) may be written in the form

$$\alpha = \frac{1}{2}\frac{\tan\phi_1}{\cos\phi_1} + \frac{1}{2}\tanh^{-1}\phi_1. \tag{A.6}$$

The rate of the deflection Z in the horizontal plane is

$$\frac{dZ}{ds} = \sin\phi. \tag{A.7}$$

But Equation (A.5) is not readily solved for ϕ. Therefore write

$$\frac{dZ}{ds} = \frac{dZ}{d\phi}\left(\frac{d\phi}{ds}\right) = \sin\phi, \tag{A.8}$$

which on substitution of Equation (A.4) for $d\phi/ds$, yields

$$\frac{dZ}{d\phi} = \frac{H_0}{R}\frac{\sin\phi}{\cos^3\phi}; \tag{A.9}$$

for which the solution is

$$Z = \frac{1}{2}\frac{H_0}{R}\tan^2\phi, \tag{A.10}$$

and the maximum deflection per unit length z_1 is given by

$$z_1 = \frac{Z_1}{S} = \frac{1}{2}\frac{H_0}{RS}\tan^2\phi_1$$

$$= \frac{1}{4}\frac{\tan^2\phi_1}{\alpha}. \tag{A.11}$$

Since ϕ_1 (α) can be found from Equation (A.5), z_1 can be determined in terms of α. Also, the span, X_1, is given by

$$\frac{X_1}{S} = x_1 = 2\left(\frac{1}{2}\frac{\tan\phi_1}{\alpha}\right) \qquad \text{(A.12)}$$

which with Equation (A.6), yields

$$x_1 = 2\sqrt{z_1/\alpha}. \qquad \text{(A.13)}$$

From Equation (A.6), for small ϕ_1,

$$\alpha \simeq \phi_1$$

and Equation (A.11) reduces to

$$z_1 = \frac{1}{4}\phi_1 = \frac{\alpha}{4} \qquad \text{(A.14)}$$

or

$$Z_1 = \frac{RS^2}{8H_0},$$

the equation for the sag of a parabola.

Solutions to Equations (A.6), (A.11) and (A.14) are plotted on Figure A.1. Examination of Figure A.1 shows that the approximate solution, Equation (A.14), can be used with good accuracy for values of ϕ up to 20 or 25 degrees, or values of α up to 0.1.

A.3.3 Effect of an Oblique Current

Referring to Figure A.2, the curvature of an array in an oblique current is given by

$$\frac{d\varphi}{ds} = \frac{R}{T}\cos^2(\Phi - \varphi), \qquad \text{(A.15)}$$

where Φ is the inclination of the current relative to a normal to the undeflected array and φ is the angle subtended by a line tangent to the curve of the array and the undeflected axis. Here we use the tension, T, as H is no longer a constant over the length of the array. We note that the curvature is always less than that of the array in a current normal to the undeflected axis, as the

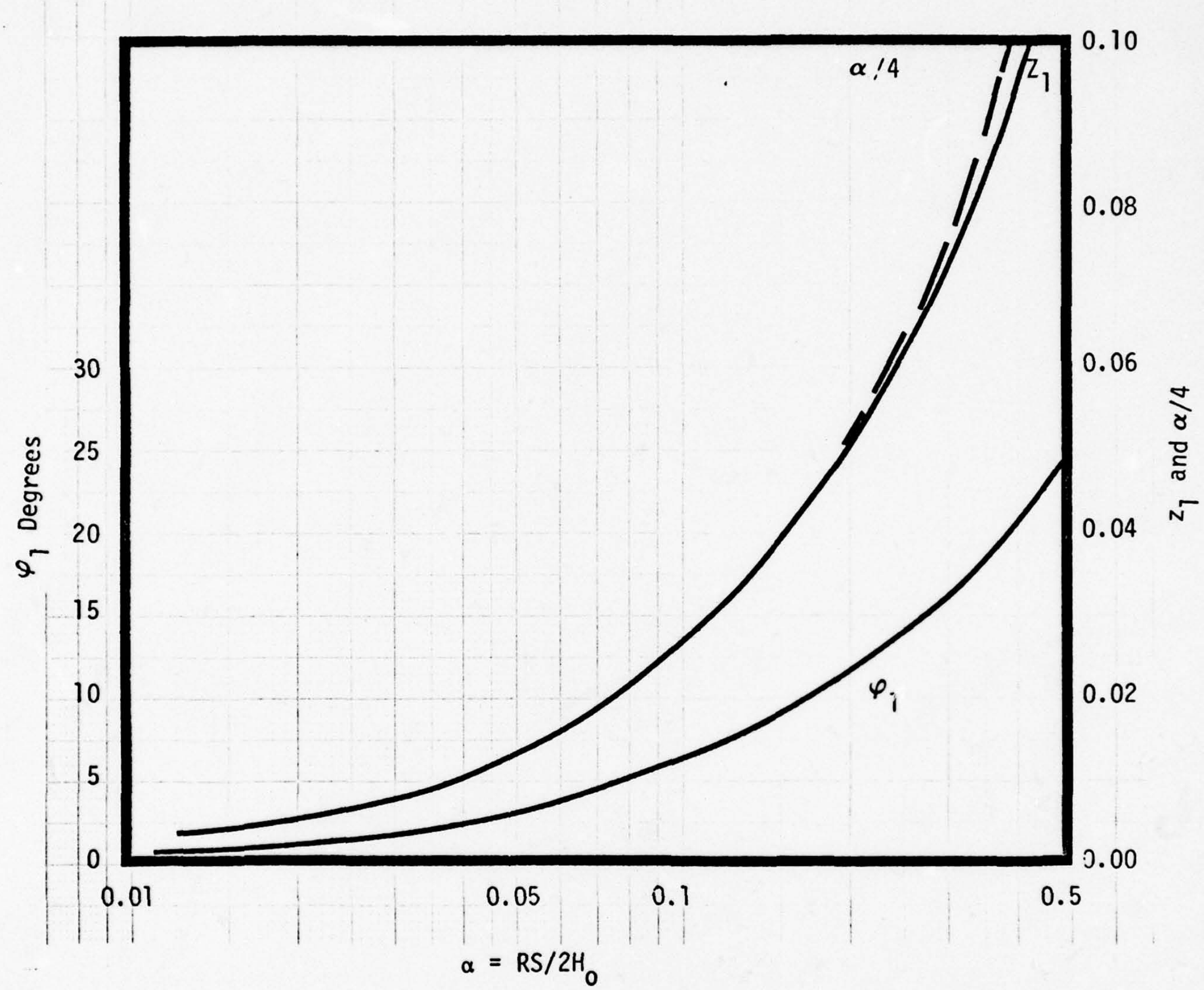

Figure A-1. Comparison of Exact and Approximate Array Maximum Deflections (z_1 is the exact and $\alpha/4$ is the approximate solution)

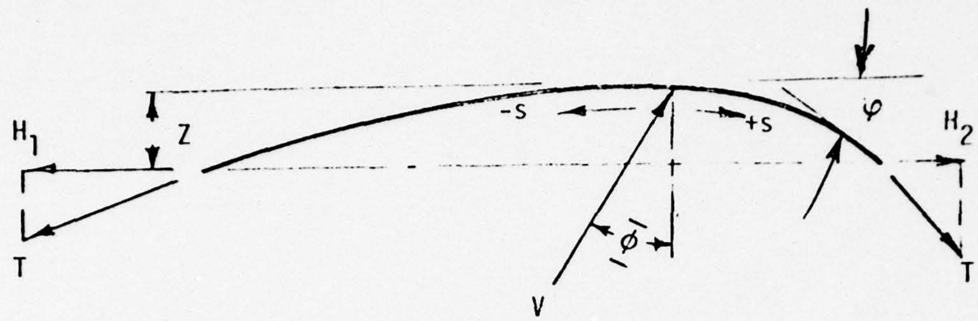

Figure A.2. Schematic of the Array in an Oblique Current

maximum curvature in the later case is R/H_o, and in the case under discussion is R/T. Since $T > H_o$

$$R/T < R/H_o$$

and the maximum deflection of the array in an oblique current can never exceed that of the array in a current normal to its undeflected shape.

A.4 EFFECT OF CURRENT ON STATIC POSITION OF THE SUSPENSION CABLES

Assume the array suspended as in Figure A.3. The horizontal reaction on the support rope due to a current is RS/2.* Assuming a uniform current and the support rope of length ℓ to be inextensible, the end of the support must execute an arc in z-y plane. Thus

$$\ell^2 = Z^2 + (Y_o - Y)^2 + \ell^2 \cos^2 A_o.$$

Recognizing that $Y_o/\ell = \sin A_o$,

$$z^2 - 2 \sin A_o\, y + y^2 = 0; \qquad \text{(A.16)}$$

where $z = Z/\ell$ and $y = Y/\ell$.

Also,

$$\tan A = \frac{\ell \sin A_o - Y}{\sqrt{\ell^2 \cos^2 A_o + Z^2}},$$

*Assuming small deflections.

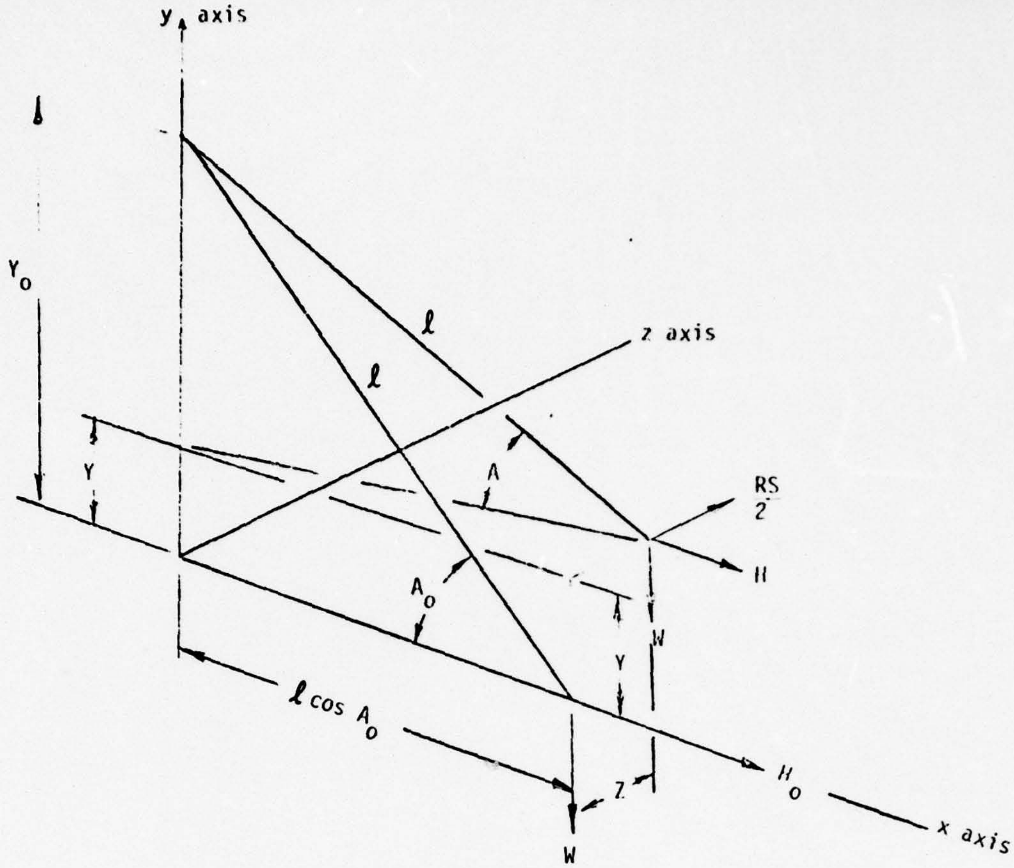

Figure A.3. Schematic of Array Suspension Deflected by Current

which may be expressed as

$$\tan A = \frac{\tan A_o - y/\cos A_o}{\sqrt{1 + z^2/\cos^2 A_o}}. \tag{A.17}$$

The assumption that array deflection is small results in

$$z/\cos A_o = RS/2H_o = \alpha.$$

Solving Equation (A.14) for y, one obtains

$$y/\cos A_o = \tan A_o - \sqrt{\tan^2 A_o - z^2/\cos^2 A_o},$$

which may be put in the form

$$y/\cos A_o = \frac{W}{H_o} - \sqrt{\left(\frac{W}{H_o}\right)^2 - \alpha^2}.$$

Recognizing that

$$\tan A = (W/H)\Big/\sqrt{1 + \alpha^2}$$

and using the above relations in Equation (A.17), the following result is obtained:

$$\frac{H}{H_o} = \sqrt{1 + \left(\frac{RS}{2W}\right)^2} . \qquad \text{(A.18)}$$

Since $\alpha = RS/2H_o$, we may write

$$\alpha = \alpha_o\Bigg/\sqrt{1 + \left(\frac{RS}{2W}\right)^2} \qquad \text{(A.19)}$$

where $\alpha_o = RS/2H_o$.

Thus, the effect of sway is to stiffen the array.

Appendix B

THE HYDRO-GLIDER

The Conceptual Design of a Parawing for Underwater Operations

B.1 GENERAL

The hydro-glider is a gravity powered vehicle which employs a Rogallo-type wing for lift generation. The vehicle is designed to carry a payload under water to a remote location. Its flight path is laterally controlled by either a rudder or by wing tilt. In either case, the control system which commands this lateral turning receives signals from a remotely located (acoustic) source. These signals are processed and the control actions initiated when and how the system's logic dictates.

The preliminary design, described in this appendix, has considered several aspects of the total system. Such items as transportability of the glider; its erection and launching; performance and control during flight; and its guidance have all received consideration. Comments relative to each of these will be found in the following paragraphs.

In addition, information pertaining to the layout and sizing of the glider canopy has been included.

B.2 THE HYDRO-GLIDER SYSTEM

Conceptually the glider is to be a low cost, small storage volume vehicle having minimum operations requirements. This is interpreted to mean a vehicle which is easily stored and transported, is unsophisticated in its operation, and can be considered as expendable if necessary. The primary purpose of the glider is to carry a "messenger line" from one fixed location to another under polar ice. Because of its operational characteristics it has the need for only simple control logic and circuitry. However, because of the environment in which it must operate there are some special requirements which must be considered in the design. These will be noted in the several sections of this appendix.

B.2.1 An Overview of the Glider During Its Operation

One reason for choosing the parawing glider is that it can be folded into a relatively small volume package when not in use. Since it is to be operated under polar ice, it was apparent that an erectable structure — one which could be unfolded and launched under the ice shelf proper — was most desired. Accordingly, the glider is introduced into the sea through a hole in the ice. It is guided into a launch position by means of the launching frame. There it is erected (remotely), using shock cords, and secured by means of frame latches. Then it is aimed and released. Subsequently, it is controlled during flight by the logic circuit designed for response to homing signals sent out from the terminal station, or "pinger." (A schematic showing various segments of this operation is found on Figure B.1. A brief discussion on the use of the launch frame is found on Figure B.2. However, details of this construction, etc., are beyond the scope of the present effort.)

The first sketch illustrates the glide sequence from "launch" to "terminal spiral." One should note that the major portion of this flight operation occurs as an equilibrium glide. During this phase of the maneuver, the glider is under command of the control system. Its function is to guide the hydro-glider toward a "capture line," which has been previously lowered into the ocean at the terminal point. On arrival there the glider is commanded to spiral around the "capture line," thereby providing a means for bringing the messenger line to the surface through this second ice hole.

Since there is a relatively large drag associated with the towing of a line through water, it was decided that the messenger line should be payed out from the hydro-glider. This enhances the vehicle's performance and removes one additional hazard from the operation (namely, fouling the line on the ice).

On the off chance that the glider and/or messenger line should not make contact with the capture line, then the hydro-glider could be pulled back to the launch position. If this is not feasible, it could then be cast free as an expendable item, and a second launching undertaken. Under all but extreme circumstances it is felt that the proposed system will function satisfactorily. Of course, proof tests are suggested as the means of verifying the design.

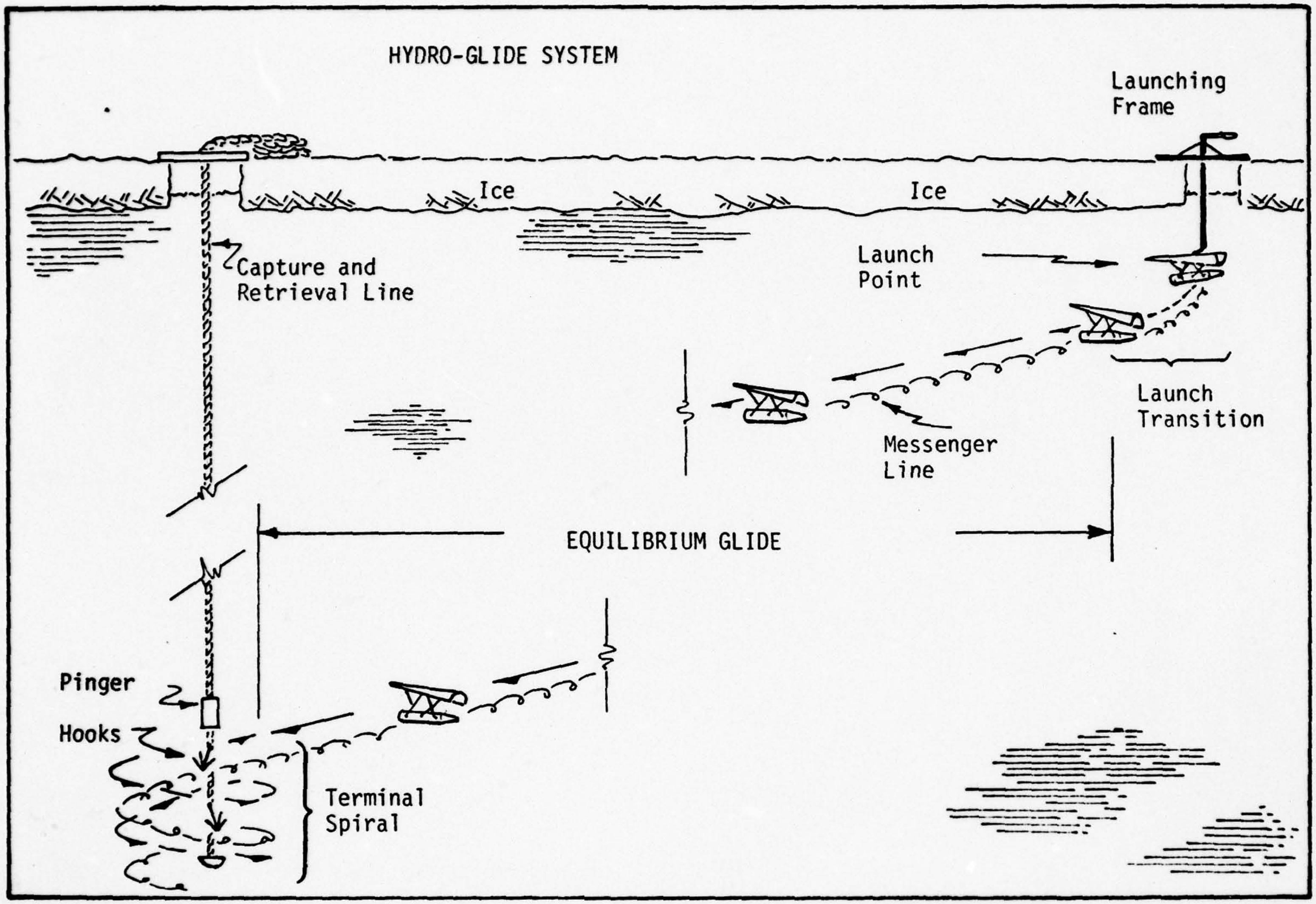

Figure B.1. Schematic of the Hydro-Glide Operation

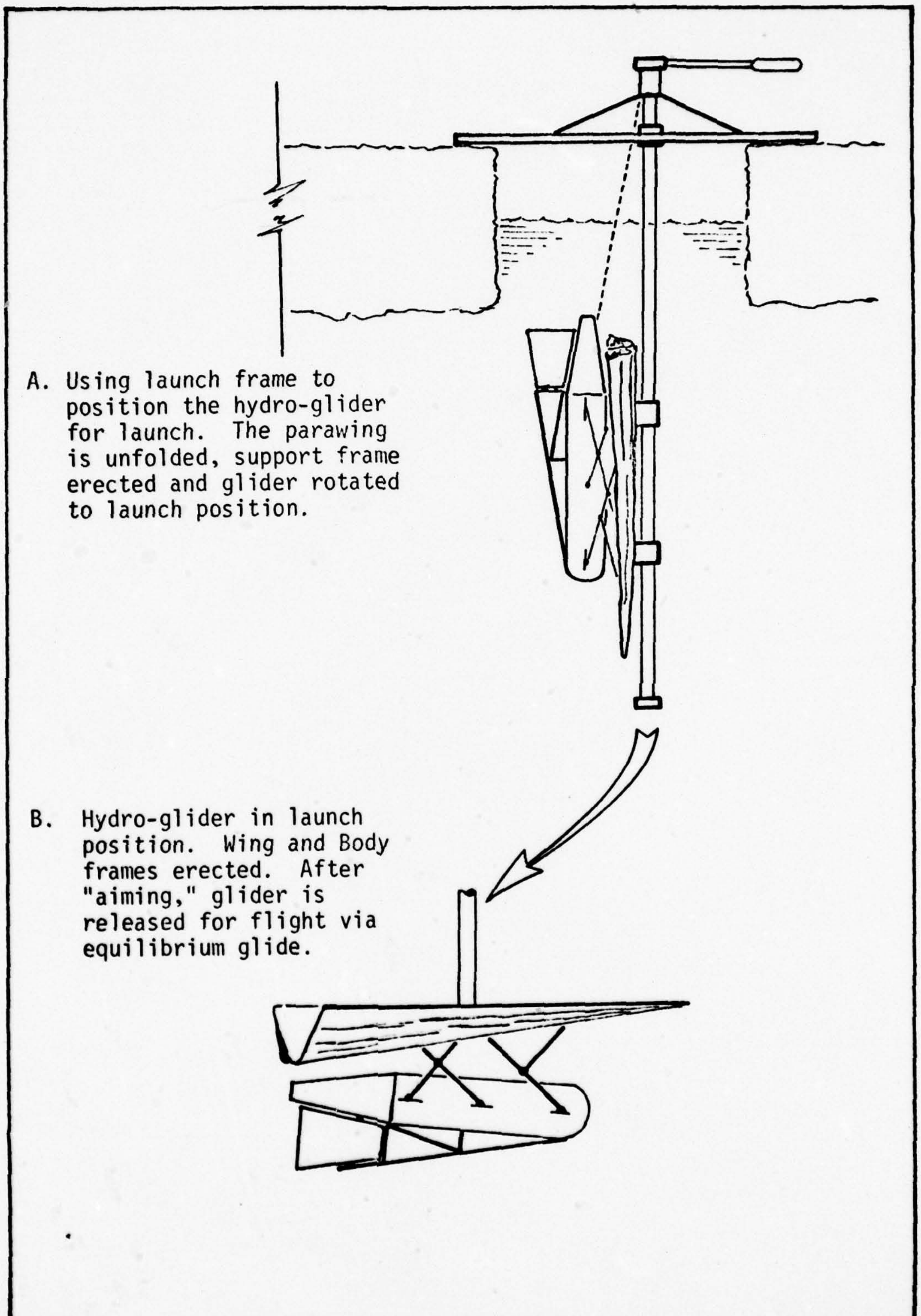

Figure B.2. Schematic of Launch Frame and Its Use

B.3 THE PARAWING CANOPY DESIGN

Designing a canopy for the hydro-glider is not a difficult task. There is a sizeable collection of experimental data available on parawings. Their aerodynamic characteristics are rather well known, and information on several prototype systems can be found in the open literature.

Following from a perusal of the literature the canopy design was selected. Basically, the planform layout is as shown on Figure B.3a. However, the specifics of this design are to be determined from an analysis of the system's performance. Nevertheless, the selected canopy geometry is that depicted on this figure.

The keel and leading edge lengths have a common dimension. This greatly simplifies the area and aspect ratio description.

Since rigid leading edges are proposed, then it follows that the inflated canopy will have two lobes, each approximating a conical surface segment. The design (chosen) is to have a semi-apex angle of $\pi/4$ (i.e. $\Theta = \pi/4$) for the flat surface. However, when inflated the canopy will be designed so that the sweep angle (φ) is set at 50^o (see Figure B.3b). To better describe the canopy, Figures B.3c and B.3d are included. Here one sees front and side views of the inflated (or loaded) canopy. Note that the leading edge members and the keel longeron are held in their relative positions by means of a spreader bar.

The canopy (proper) will be constructed from some flexible material, such as nylon, dacron, etc. The material must be lightweight; it must be free to form the typical parawing lobed shape, and be able to do so in the Arctic environment.

B.3.1 Other Design Features

Figure B.3e shows, in schematic, the supporting frame, payload cab and rudder for the hydro-glider. Notations are provided on this sketch in explanation of these several components. There is a likelihood that the rudder system may be replaced by a wing (canopy) tilt mechanism for lateral control. In this case, the support structure would be joined to the keel by a hinged coupler. This coupler would allow a rolling of the canopy, thereby providing yaw (lateral) control.

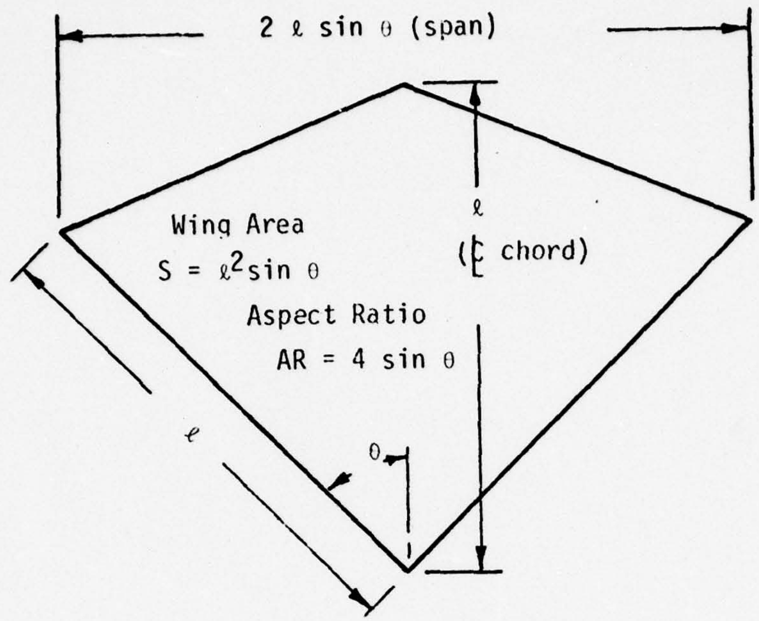

Figure B.3a. Top View of Flat (Uninflated) Canopy

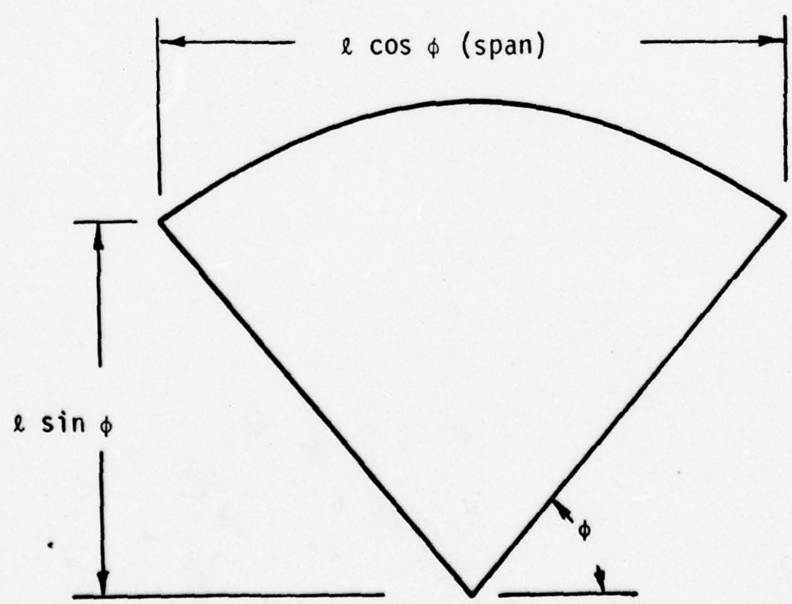

Figure B.3b. Top View of Inflated Canopy

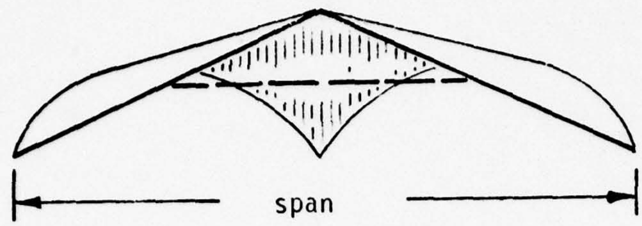

Figure B.3c. Front View of Inflated Canopy

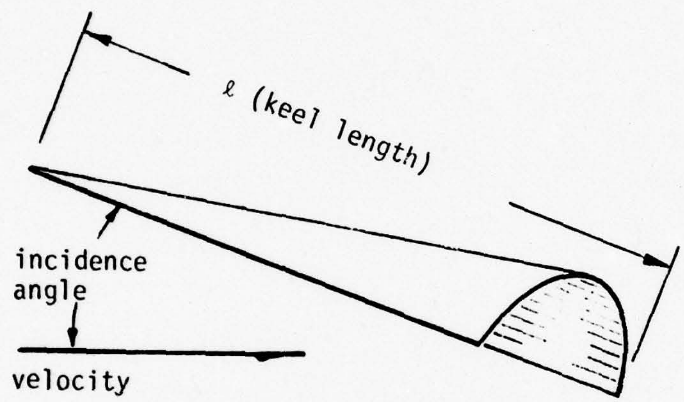

Figure B.3d. Side View of Inflated Canopy

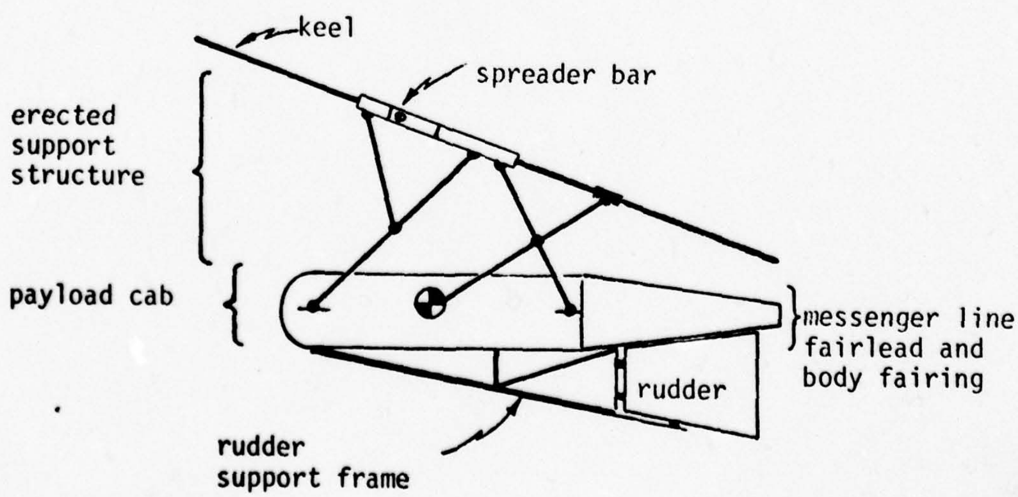

Figure B.3e. Schematic Showing Keel, Related Structure and Optional Rudder

B.3.2 Aerodynamic Characteristics of the Hydro-Glider

An aerodynamic description of the glider can be acquired rather easily from the available research literature. In particular, the design is primarily described in two basic references* (References 1 and 2).

Figures B.4a and B.4b describe this design aerodynamically. In addition, there are curves included on Figure B.4a to show the influence of support structure and canopy geometry on the aerodynamic efficiency (lift-to-drag ratio) of this lifting surface type. There it is seen that a decrease in aspect ratio, as well as the inclusion of non-lifting support members, has a debilitating influence on the aerodynamic efficiency. (These data were extracted from References 1 and 2.)

The information shown on Figure B.4b is the basis for the proposed design. These aerodynamic parameters are judged to describe the hydro-glider. Here the multiple influences for structure, payload cab and lifting surface are considered to be present. These data have been developed from information contained in Reference 2.

It should be mentioned that the aerodynamic efficiency of this design could be enhanced by choosing a cylindrical canopy rather than the conical one. However, the support structure for the cylindrical canopy is more complicated, and the storage of each unit would require a larger volume. In view of the added complexities involved, the conical, two lobe canopy was chosen.

B.3.3 Flight Stability for the Hydro-Glider

According to the literature, the present design possesses sufficient stability (both longitudinally and laterally) to maintain its proposed equilibrium glide path. In addition, there is an adequate control capability available, using either rudder control, or wing tilt, to make all the needed lateral maneuvers. (For details, the reader should consult the literature.) Insofar as can be ascertained, this parawing system will maintain its glide and be able to turn, as needed, so long as the c.g. remains near the 50% keel position

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*[1]Polhamus, Edward C. and R. L. Naeseth: Experimental and Theoretical Studies of the Effects of Camber and Twist on the Aerodynamic Characteristics of Parawings. NASA TN D-972, 1963.

[2]Johnson, Joseph L., Jr.: Low-Speed Wind-Tunnel Investigation to Determine the Flight Characteristics of a Model of a Parawing Utility Vehicle. NASA TN D-1255, 1962.

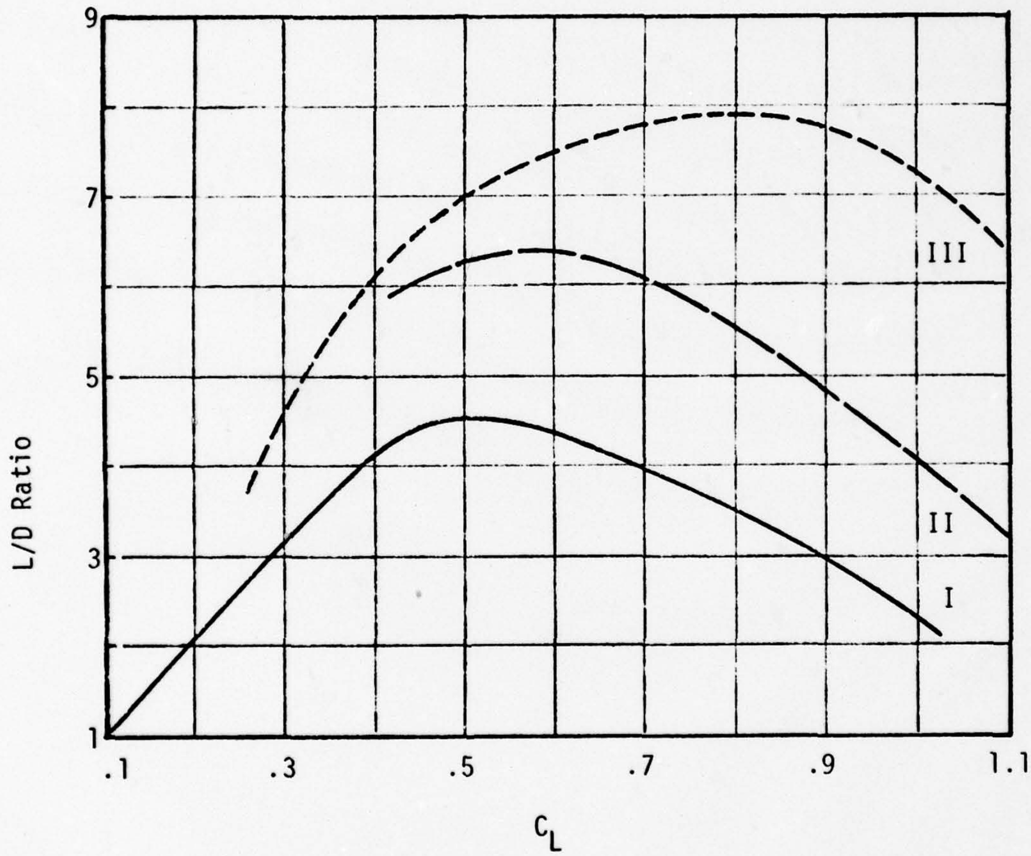

Figure B.4a. Comparison of Lift-to-Drag Ratio for
I - Full Model with Conical Canopy:
II - Conical Canopy (AR ≃ 3) Alone;
III - Conical Canopy (AR ≃ 6)

MODEL CHARACTERISTICS

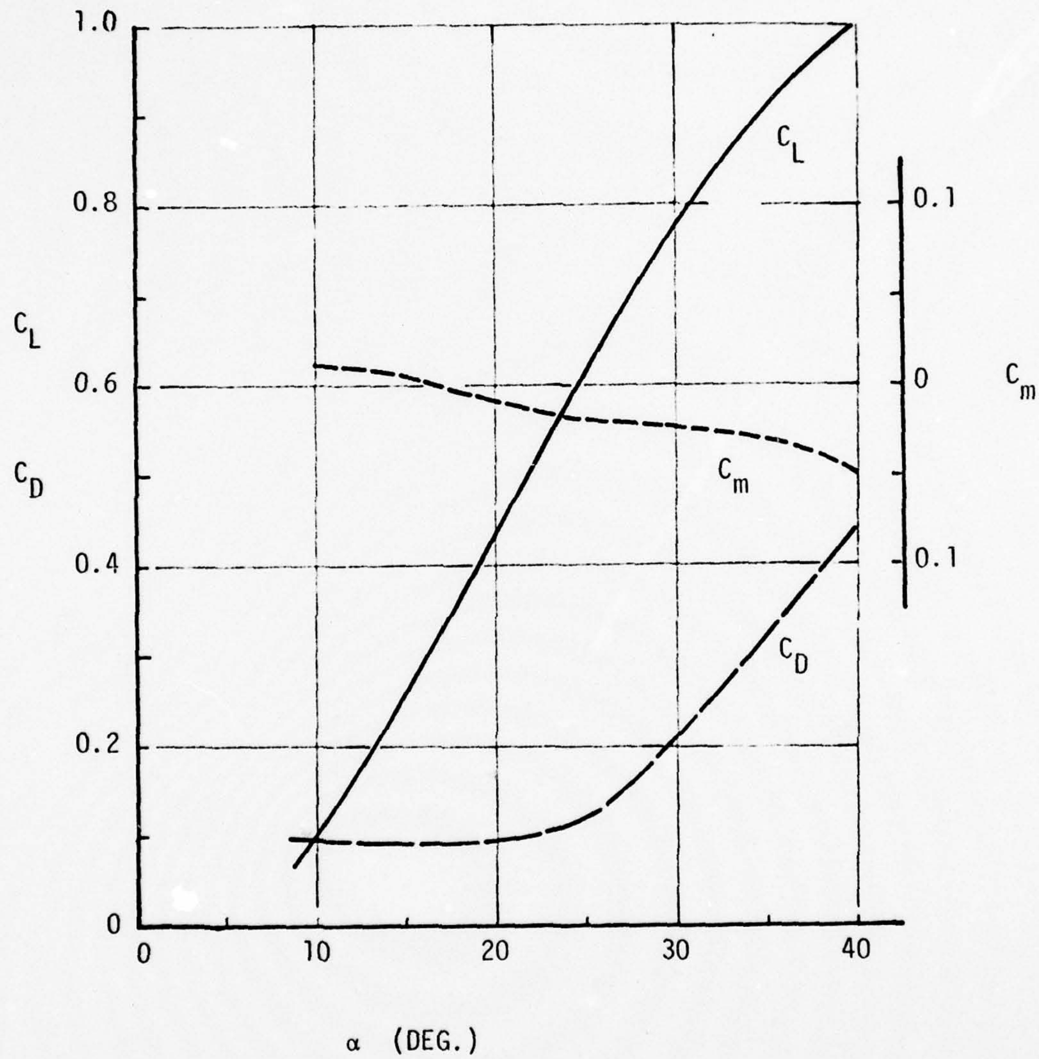

Figure B.4b. Lift, Drag, Pitching Moment Coefficients for Hydro-Glider Model (AR ≈ 3). Moment Center is c.g.

(longitudinally) and in the vicinity of 25% (of keel) below the keel line. There should be approximately an 8% c.g travel allowable for this design configuration.

Bank angles of up to 15^{o} could be achieved by the hydro-glider without loss of control or stability. Angles of attack ranging from 10^{o} to 40^{o} should be attainable for the hydro-glider. However, mission dictates for this design suggest an operating angle of attack at approximately 22^{o}. (This will be demonstrated later.)

B.4 HYDRO-GLIDER PERFORMANCE

Performance parameters are readily determined from an examination of the general expressions describing the flight path, coupled with aerodynamic data describing the vehicle's characteristics.

Thus, using the information found on Figure B.4b, and the governing equation listed below, the glide and turn performance of the hydro-glider can be estimated.

B.4.1 Equation of Motion — Gliding Flight

A description of the quasi-steady flight of a glider, in the local vertical plane of motion, can be expressed as follows:

From kinematics:

$$\dot{X} = V\cos\gamma,$$
$$\dot{h} = V\sin\gamma. \qquad \text{(B.1)}$$

A balance of forces gives:

$$L = W\cos\gamma,$$
$$D = -W\sin\gamma. \qquad \text{(B.2)}$$

The assumption of fixed weight (W) is used. Messenger line payout from the glider is slow; also, weight loss is only 8 lbs (3.6 kg) total.

In these expressions, X, h are the horizontal and vertical displacements; γ is the flight path angle ($\gamma < 0$ defines gliding); L, D and W are vehicle lift, drag and weight, respectively. A dot superscript infers a time derivative.

It is presumed here that the aerodynamic forces are defined in terms of their respective coefficients according to:

$$F = C_F \frac{\rho V^2}{2} S \qquad (B.3)$$

where C_F is the aerodynamic force coefficient; ρ is the fluid mass density; and S is a reference area for the vehicle (herein S is the flat canopy area — see Figure B.3a.)

Since p rawings do not have a well defined drag polar, the analysis used to obtain performance parameters assumed a general relationship — i.e. $C_D \equiv C_D(C_L)$.

Additionally, to aid in generalizing this analysis, a reference speed (V_{ref}) has been introduced. This is a fictitious speed corresponding to level flight at $C_L = 1.0$. All subsequent flight operations will be expressed in terms of a speed ratio ($u \equiv V/V_{ref}$), the aerodynamic efficiency ($E \equiv C_L/C_D$), and other parameters descriptive of the vehicle and its glide maneuvers.

After manipulating the several equations set down above, it was found that the glide path for this vehicle could be described as follows:

(a) A determination of the glide angle is obtained as:

$$\gamma = -\sin^{-1}[1 + E^2]^{-1/2} \qquad (B.4)$$

(b) The sinking speed ($\dot{h}$) is determined from:

$$\frac{\dot{h}}{V_{ref}} = -\frac{1}{E\sqrt{C_L}} \left(\frac{E^2}{1 + E^2}\right)^{3/4} \qquad (B.5)$$

(c) The speed ratio, u, is found to be:

$$u = \frac{1}{\sqrt{C_L}} \left(\frac{E^2}{1 + E^2}\right)^{1/4} \qquad (B.6)$$

(d) The horizontal range for the glider is defined from:

$$X = E h, \qquad (B.7)$$

where h defines the change in depth achieved during the glide operation.

(e) The "time of flight," or duration of the equilibrium glide is described by:

$$t = \frac{E\sqrt{C_L}\, h}{V_{ref}} \left(\frac{1 + E^2}{E^2}\right)^{3/4} \qquad (B.8)$$

B.4.2 A Generalized Representation for Glide Performance

In order to generalize the above expressions, and to have them represent the hydro-glider over its entire operating range, non-dimensional performance parameters are utilized.

Since each operating point for the hydro-glider can be presumed to occur at a fixed C_L, hence a fixed α (angle of attack) and constant E, then an appropriate set of performance parameters may be described as:

u (the speed ratio),

$-\dot{h}/V_{ref}$ (the dimensionless sinking speed),

X/h (the horizontal range to depth-change ratio),

and $t\,V_{ref}/X$ (the dimensionless time of flight).

In addition, the glide path angle (γ) and operating angle of attack are desired and important descriptors of the operations. For convenience and consistency, all the performance will be described in terms of α (the operating point) angle of attack. See Figures B.5a and B.5b.

One necessary parameter remains to be defined — that is the reference speed (V_{ref}). Recalling this is defined as a fictitious speed, for horizontal flight at C_L = 1, then

$$V_{ref} = \sqrt{\frac{2}{\rho}\frac{W}{S}}. \tag{B.9}$$

This parameter is plotted against the wing loading (W/S) on Figure B.5c. For nomenclature, the speed is given in knots, while the loading is expressed in (both) lbs/ft^2 and kg/m^2 (see scales on the figure).

Use of these figures for determining the glide performance will be illustrated subsequently in a sample situation (see the section titled, "Performance Estimation and Vehicle Sizing," below).

B.4.3 Turning Flight Performance

To this point in the analysis only the equilibrium glide has been considered. There remains one other maneuvering capability which should be described for the hydro-glider. This is the lateral (quasi-steady) turning situation.

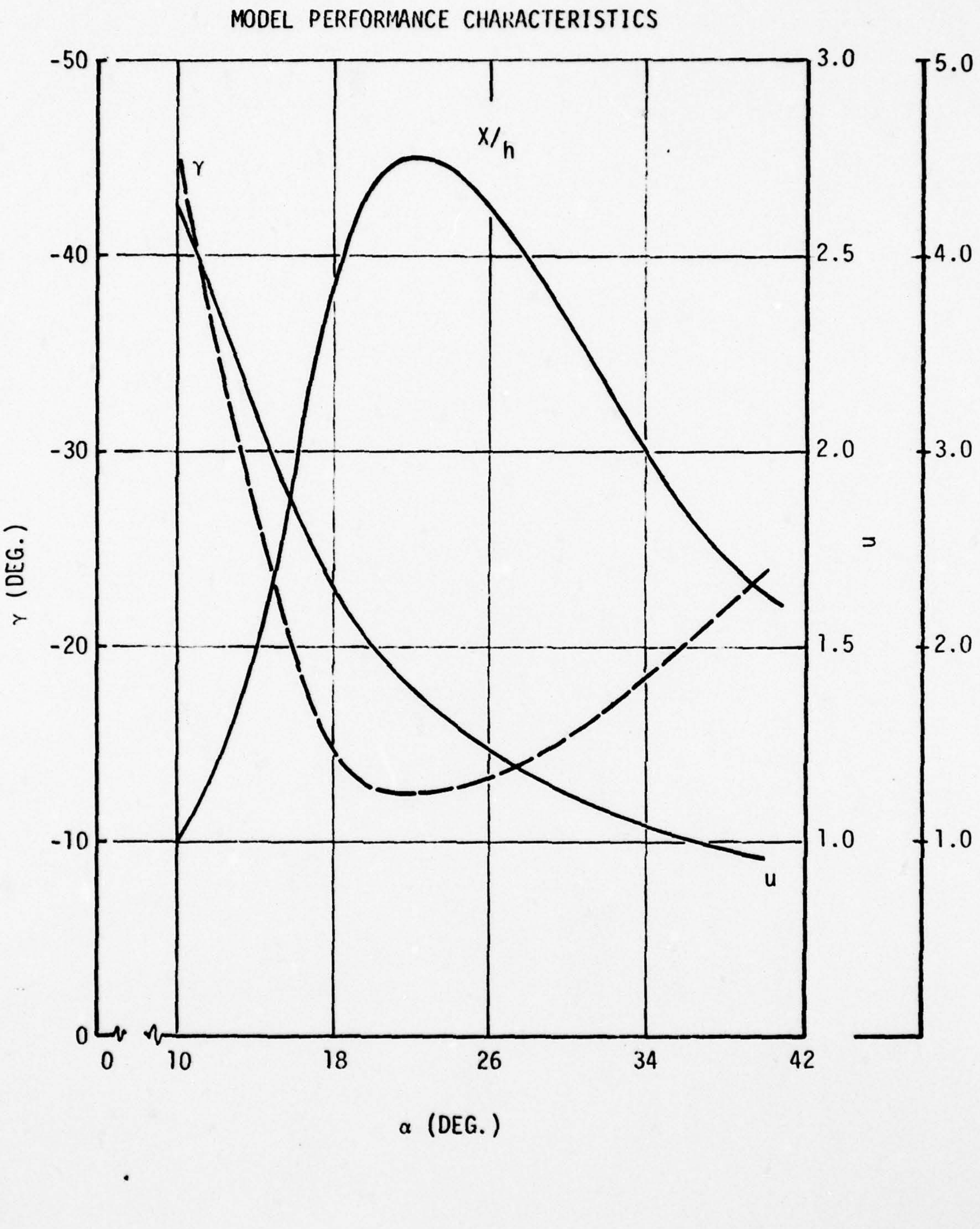

Figure B.5a. Performance Parameters Developed for Full Model (AR ≈ 3) in Equilibrium Glide

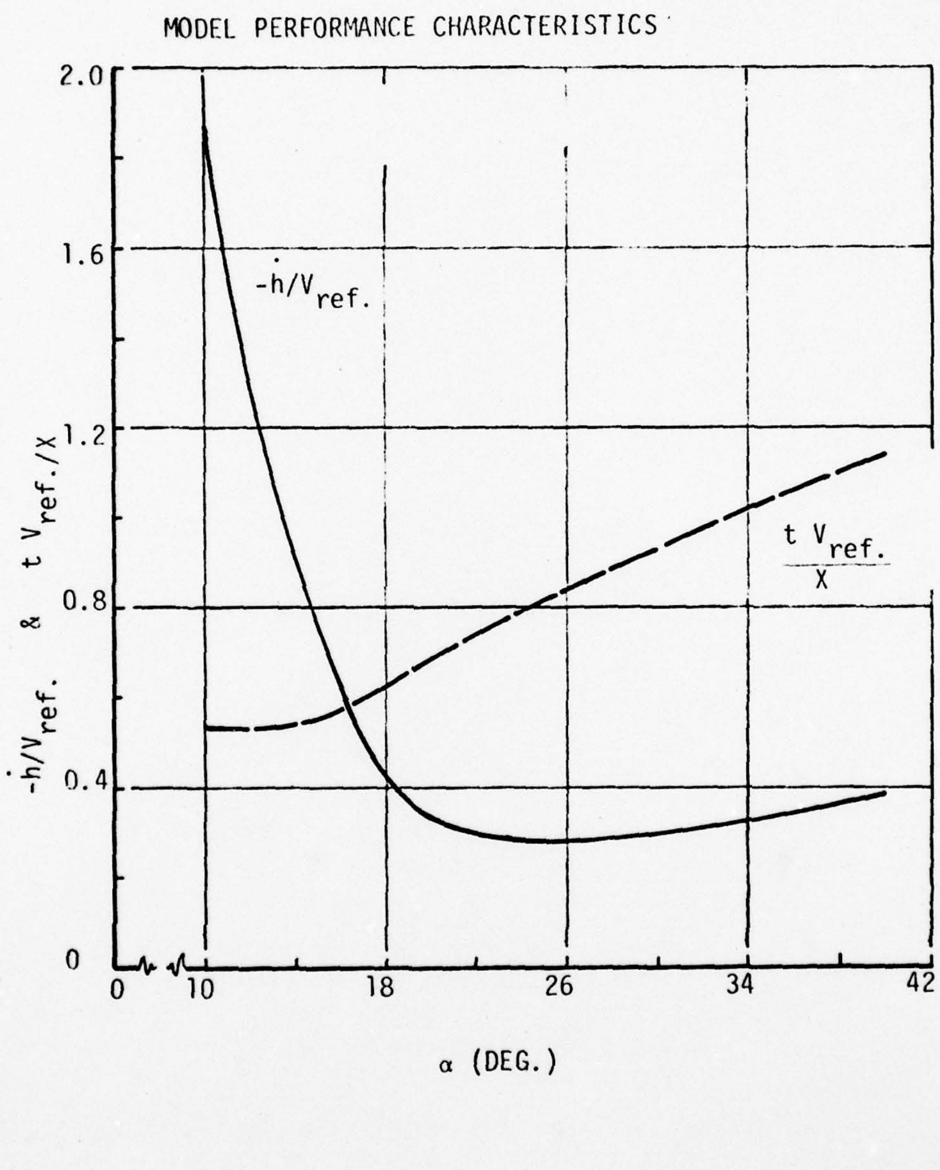

Figure B.5b. Performance Parameters Developed for the Model Hydro-Glider in Equilibrium Glide

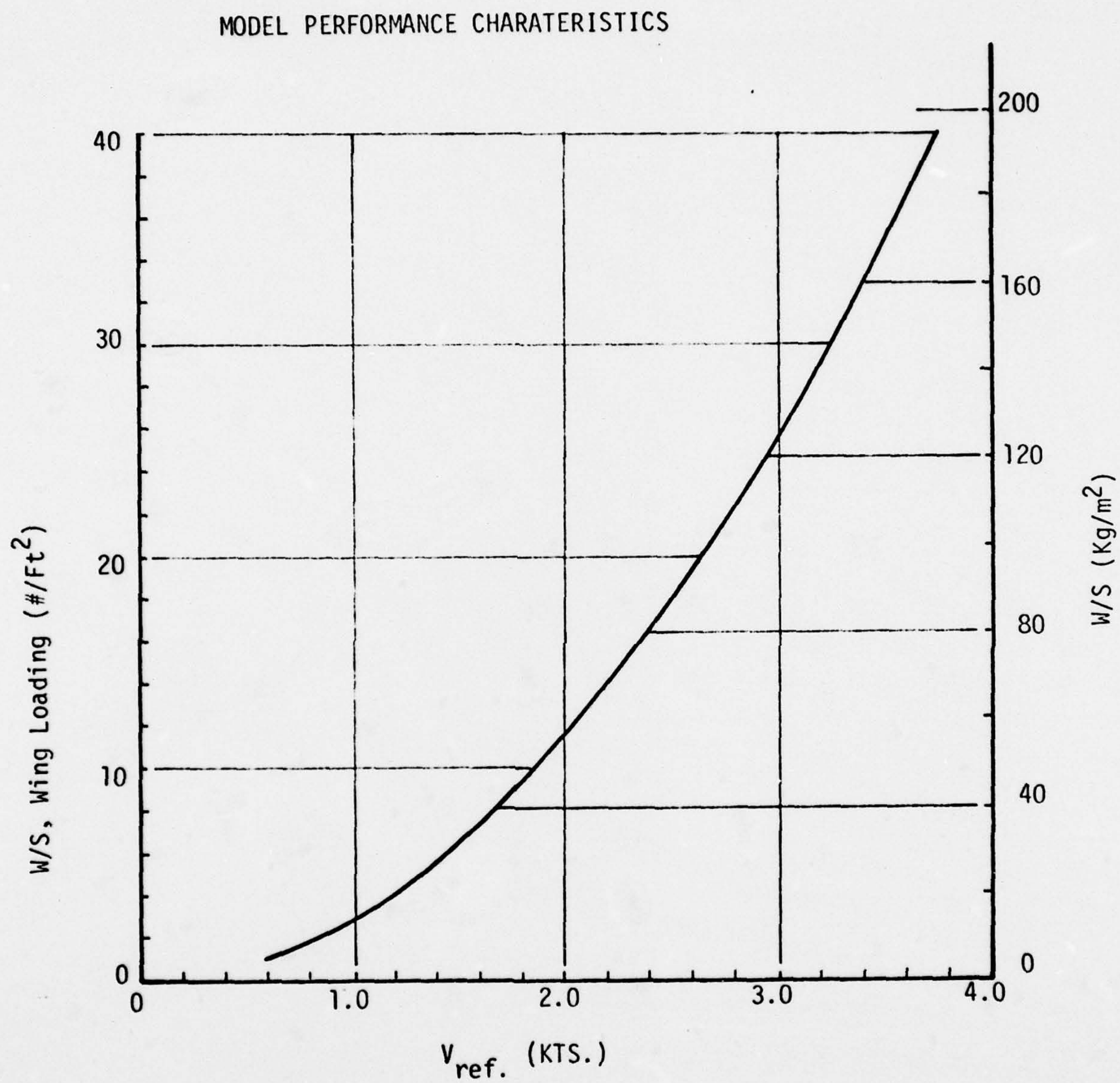

Figure B.5c. Description of Reference Speed in Terms of Wing Loading

For this maneuver a banked turn will be described. The purpose here is not to design the control, per se, but to ascertain a capability in turning flight for the hydro-glider.

Banking of the glider is undertaken so that the lift vector can be "tilted" to null the centrifugal force. Hence, the quasi-steady turning (yaw) rate expression can be shown to be:

$$\dot{\psi} = \frac{g \cos \gamma \tan \phi}{V}, \tag{B.10}$$

where ϕ is the bank angle.

Similarily, the radius of curvature for a banked turn is readily found from:

$$r = \frac{V^2}{g \cos \gamma \tan \phi}. \tag{B.11}$$

B.5. CLOSURE

The various expressions shown above describe glide performance for this design under a quasi-steady flight condition. It should be recalled that there will be a "transition" at launch and another at the initiation of the "terminal spiral" (see Figure B.1 for nomenclature). These are non-linear flight operations not examined in the context of this preliminary evaluation.

B.6 FLIGHT GUIDANCE AND CONTROL

It has been mentioned earlier that guidance and control capabilities will be needed for the hydro-glider. These are necessary if the glider is to successfully reach its desired terminal location and thereby complete its intended task.

Basically, the guidance scheme proposed for the hydro-glider is one which will take the vehicle along a circular arc. Deviations from this nominal path will be sensed. The error signals, acquired by the proposed control system, will be processed and converted into a control action — one which will tend to return the glider to its nominal path. On reaching the terminal locus, the control system will initiate an action to produce the "terminal spiral," thereby completing the maneuver.

A description of this control system follows below.

B.6.1 Control System Description

The control system will utilize two wing mounted hydrophones to measure a difference in pulse arrival time from the acoustic pinger; and to develop an error signal based on this time difference. The error signal will drive a DC stepping motor which will activate the control surface and direct the vehicle toward the acoustic source.

As shown in Figure B.6, the received acoustic pulse from the hydrophone is sent to a bandpass filter, AGC amplifier, and detector. For optimum detection, the filter bandwidth should be matched to the bandwidth of the acoustic pulse. The approximate bandwidth of this pulse is BW = 1/T, where T is the pulse duration which will be determined by the maximum heading deviation expected from the vehicle. For example, with a vehicle deviation of 25^o and a sound velocity of 5,000 ft/sec, T would equal approximately 300 micro seconds, giving a filter bandwidth of 2.5 kHz. If this is the maximum expected deviation, then the pulse duration can be lengthened and the corresponding filter bandwidth decreased to improve the S/N ratio in the detector circuitry, when noise only is present at the input, making it possible to select an optimum fixed reference voltage for the comparators at the detector output.

The timing diagram, Figure B.7, shows the output of these comparators as PR and PL, where PR is displaced in time corresponding to a right wing forward condition. An exclusive OR gate is used in conjunction with a latch to determine the first pulse to arrive, and to measure the difference in arrival times between left and right pulses. The output of this exclusive OR circuit (LD) is used to gate clock pulses (CD) to a synchronous UP/DOWN counter where the clock frequency is selected so that each pulse represents one degree of heading error. The first pulse arrival generates a turn right or turn left signal (TR, TL) which determines the direction of count. The pulse turn-off transition is used to reset the latch (TE) and hold it off until the next pulse is received. The output of the synchronous counter, which is now a number proportional to left or right heading error, is stored in a buffer and then gated to the stepping motor at 500 steps per second. After one second, a carry pulse is generated — this transfers the next count to the buffer and presets the synchronous counter. This preset is used to establish an input count bias which will offset the vehicle heading a predetermined number of counts (degrees).

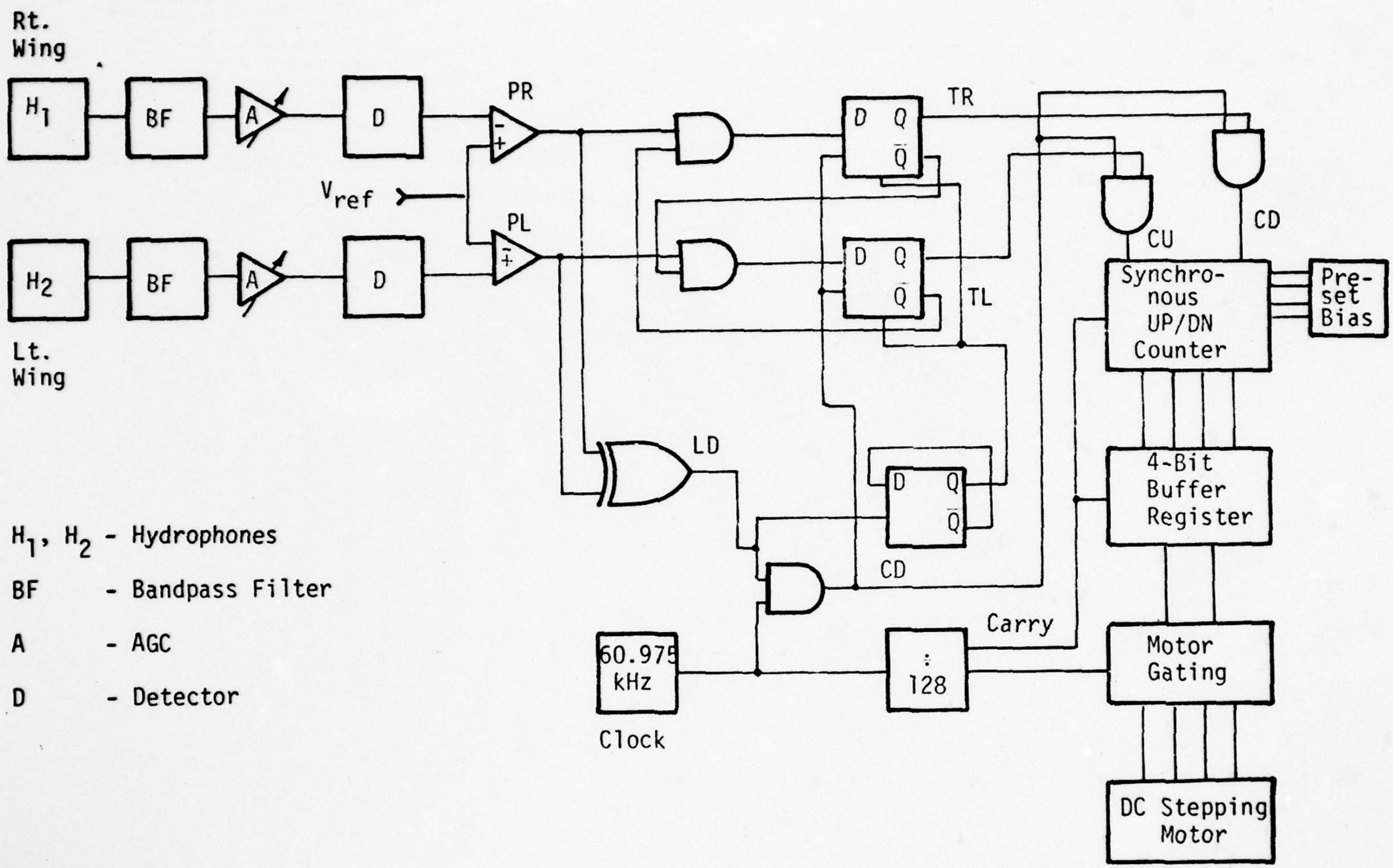

Figure B.6. Schematic of the Control System Proposed for the Hydro-Glider

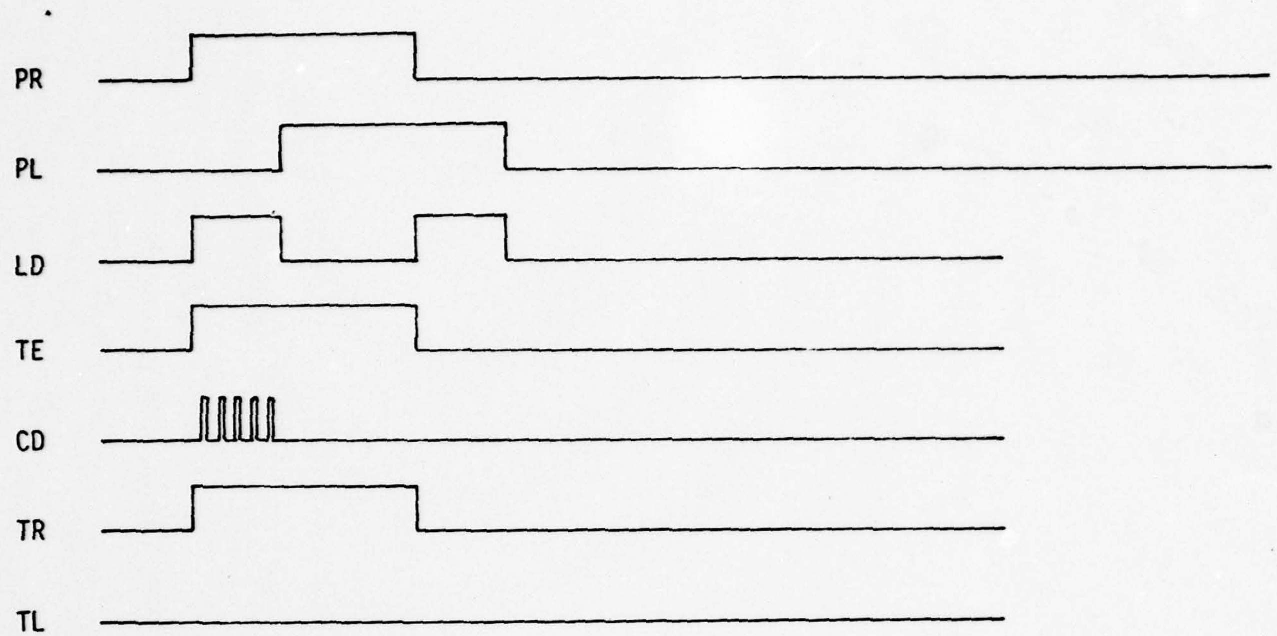

Figure B.7. Timing Diagram for the Hydro-Glider Control System

High reliability for this system is achieved by utilizing digital techniques for most of the control circuits. These can be implemented entirely with standard integrated circuits. Where possible CMOS technology will be used for low power consumption and high noise immunity, with military temperature range (-55 to +125^o C) components used throughout.

B.7 PERFORMANCE ESTIMATION AND VEHICLE SIZING

In order to establish a more coherent estimate of the hydro-glider's size and performance, some numerical results will need to be established.

For a beginning, let it be assumed that the vehicle should have a glide speed somewhere between 2.5 and 3.0 f/s (0.762 to 0.914 m/s).

Estimating that the total vehicle will weigh approximately 100 lbs (45.37 kg) in water, then from Figure B.5c it is found that $V_{ref} \approx 2.04$ kts for a wing loading of 12#/ft^2 (58.6 kg/m^2).

B.7.1 Establishing an Operating Point for Performance

It is well known that the best range is acquired at a least value for glide slope. Looking at Figure B.5a, it is seen that the Operating Point should be selected as $\alpha \cong 22^o$. Consequently, the design parameters for this angle of attack (from Figures B.4b and B.5a, at $\alpha = 22^o$) are:

$$|\gamma| \cong 12.5^o; \; u \simeq 1.4; \; X/h \approx 4.5, \text{ and } C_L = 0.5.$$

Also, from Figure B.5b, it is seen that

$$-\dot{h}/V_{ref} \cong 0.3, \text{ and } t\, V_{ref}/X \approx 0.73.$$

Assuming, next, that the operating change in depth for the hydro-glider is 300 fathoms, then using these numbers and the appropriate definitions, it is found that the operating point performance estimates are:

$$V_{ref} \cong 2.04 \text{ kts} = 3.445 \text{ f/s (1.05 m/s)};$$

then the glide speed,

$$V \cong 4.823 \text{ f/s (1.47 m/s)};$$

also, the sink rate,

$$-\dot{h} \cong 1.03 \text{ f/s (0.315 m/s)}.$$

Next, with

$h \cong 300$ fathoms

then, the range (during glide),

$X = 8100$ ft (2469 m), or 1-1/3 n. miles.

Since the dimensionless time is ≈ 0.73, then the "time of flight" is,

$t \cong 1716$ sec.

$= 28.6$ min.

At the terminus of the equilibrium glide, the hydro-glider is to execute its terminal maneuver — the "terminal spiral." Assume for the present analysis that lateral control is to be achieved by wing tilt, then an estimate of the yaw rate and turning radius for the terminal maneuvers are acquired from Equations (B.10) and (B.11).

Using the glide speed V ($\cong 4.823$ f/s, or 1.47 m/s), a glide slope of -12.6^o, and assuming the wing tilt to be 5^o, then the quasi-steady turn maneuver is described by:

(a) the yaw rate:

$$\dot{\psi} \cong 0.8 \text{ rad/sec.}$$

and

(b) the radius of the terminal spiral:

$$r = 4.32 \text{ ft } (1.315 \text{ m}).$$

Now, to "size" the hydro-glider, recall that the wing loading $\approx 12\#/ft^2$; then for a 100-lb weight (payload plus structure), the wing area should be 8-1/3 ft^2 (0.774 m^2).

Next, from Figure B.3a, it follows that the keel length (ℓ) should be:

$\ell \cong 3.433$ ft (1.046 m)

Also,

$AR = 2.83$ (flat canopy),

thus,

$b \cong 4.86$ ft (1.48 m).

These wing dimensions suggest an operation point center of gravity location as:

c.g at 2.43 ft (0.74 m) aft of keel nose and at 1.265 ft (0.37 m) below the keel line.

B.7.2 Closure

The above example illustrates a procedure to follow in estimating the performance of the hydro-glider and the sizing of the vehicle.

Furthermore, if one studies the performance curves, it is seen that the parameters do not vary, largely, in the vicinity of the selected operating point. This would indicate that the vehicle's response is not critically affected by small changes in the design, or by a slight shift in the operating point selection.

The preliminary design tasks are now completed; the next step would be one to develop the design and to prove the system. Feasibility has been established; performance and operations are to be demonstrated.