ARCTIC INSTRUMENTATION WORKSHOP PROCEEDINGS
UNIVERSITY OF WASHINGTON PACK FOREST
DECEMBER 4-6, 1991

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editors

Sponsored by the U.S. Office of Naval Research
and the Applied Physics Laboratory,
University of Washington

Applied Physics Laboratory 1992

FOREWORD

The Geodesic Underice Tramway System (GUTS) is being developed to support a variety of scientific investigations under the Arctic ice. The goal of a workshop held December 4-6, 1991, at the University of Washington's Pack Forest facility was to identify scientific priorities and the relevant measurement capabilities of this instrument-carrying platform. These measurements would support research programs that require detailed mapping of exterior and interior physical properties of the ice, and the water adjacent to the ice. The participants sought to evaluate scientific priorities and the instrumentation required for investigations in ice mechanics, acoustics, optics and oceanography. This report is compiled from the workshop proceedings. It was concluded that GUTS is capable of making a wide variety of measurements over time and space scales that are critical to research in these four areas.

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I. EXECUTIVE SUMMARY

Terry Ewart and Kevin Williams

The GUTS workshop provided a successful forum for communication and laid the groundwork for future cooperation on scientific investigations. The ice mechanics, acoustics, optics and oceanography sections in this report clearly define the scientific issues and assess the utility of the GUTS platform. In addition, they provide rudimentary plans for future goals and development. Much of the desired ground truth information is common to all the studies discussed; thus, measurements and instrumentation to obtain this information is of primary importance. "What needs to be measured" is identified, and we conclude that most of the proposed measurements would be viable from the GUTS platform. However, many of the measurements discussed have not been tried before, particularly non-invasive measurements of ice properties. Unfortunately, visionary ideas for instrumentation design at the meeting fell short of our expectations. "I've used this widget to good ends before - let's use it now", was a common attitude and overshadowed, "The GUTS platform represents novel capabilities which will allow us to build new widgets for making measurements". Another workshop is needed to explore new (and available) technologies for non-invasive measurements of water and ice properties.

Scientific Effectiveness

The acoustics, ice mechanics, and optics sections clearly define the measurements needed to understand the scientific issues, but give little insight into how accurately such measurements can be made in space and time. (In the oceanography section, all proposed measurements can be accomplished by technology regularly used by the participants.) The clearest science/measurement issues are: (1) measurements of ice properties that can lead to fracture mechanics models on sub-kilometer scales to much larger scales, and (2) measurements required to establish ground truth for acoustic backscattering and forward scattering predictions. It is clear that the capabilities of the GUTS platform will fit the space/time requirements for these and the oceanographic studies. It was not established however, that the oceanographic measurements proposed addressed first order arctic scientific issues. Many measurements were proposed for arctic optics, and GUTS would function as a viable platform to carry them out. It is still necessary however, to define where optical issues and non-invasive measurement issues would be symbiotic. This should be a priority at the workshop mentioned above.

Where Do We Go From Here ?

1. Establish a series of deployments and their relationship to specific large-scale scientific programs. This should include a mechanism for small-scale investigators to obtain platform time.

2. Work with ONR and principal investigators to establish a prioritized sequence of experiments that optimize the use of GUTS during each deployment.

3. Establish the final configuration for various instrument carrying platforms to be deployed.

4. Insure that data collection and storage capabilities are compatible with the current instrumentation design.

5. Continue to hold meetings to discuss new instrumentation designs and to perfect existing techniques.

II. INTRODUCTION

Terry Ewart and Kevin Williams

The Geodesic Underice Tramway System (GUTS) is being developed to make accurate transects under an ice sheet over scales to 1 kilometer. The array is designed to be used for research associated with ice and near ice physical processes. The system, shown in Figure 1, utilizes three computer controlled winches to support a tram car with a large virtual mass (entrained water) under the ice. An instrument carrier, controlled by a small winch, is buoyed up from the tram car, and will operate close to (or even contacting) the underside of the ice. The platform will be capable of running in two modes. In the first, the system is operated in linear trajectories at about 0.5 m/s^{-1}, with the instrument carrier maintained at a constant depth near, but below, the ice. In the second, the instrument carrier will stop at specified points at or near the surface. The system and its control algorithms have been modeled using the coupled differential equation solver, TUTSIM. Results demonstrate that position accuracies to a few centimeters in the horizontal and vertical directions are possible. Much of the hardware has been designed, and one of the winches is under construction.

The idea for GUTS, conceived by Terry Ewart, was inspired by an ONR Code 1125AR workshop on the development of an Arctic ice acoustic backscattering ARI. The system was viewed as a mechanism for mapping the elastic properties of ice in a deterministic sense, in order to provide environmental support for acoustic measurements. Subsequently, an ONR-supported study validated the concept, and led to system development at the Applied Physics Laboratory.

On December 4-6, 1991, Kevin Williams and Terry Ewart hosted a workshop on experiment and instrumentation design for GUTS at the University of Washington's Pack Forest facility. Participants active in optics, oceanography, acoustics and ice mechanics attended, because these disciplines were known to have research needs that could be uniquely addressed by techniques and instruments supported by GUTS. A list of the attendees and their affiliations is found on page iii. On the first morning of the workshop, selected speakers pinpointed important scientific issues within their discipline. In the afternoon following short presentations on instrumentation issues, the participants broke up into groups led by Wilford Weeks and Zednek Bazant (ice mechanics), Gary Maycut and Gary Gilbert (optics), Hendrik Schmidt (acoustics), and Tim Stanton (oceanography). The focus of each group was to identify and prioritize scientific issues and to define the required instrumentation for investigations.

This report is divided into seven parts. Section I is a short summary of the proceedings and includes recommendations for future action. Following this introduction are four parts composed of the edited versions of the workshop materials prepared by each group. (The name(s) below the section title refers to those responsible for compiling the final copy.) Issues, measurements and instruments relevant to the ice mechanics, optics, acoustics, and oceanography of arctic sea ice are discussed. The issues are not restricted to those that can be addressed by GUTS. A table included at the end of each part outlines the specific role of GUTS in addressing scientific issues. The final section is a review of the engineering progress, which is being coordinated by LeRoy Olson.

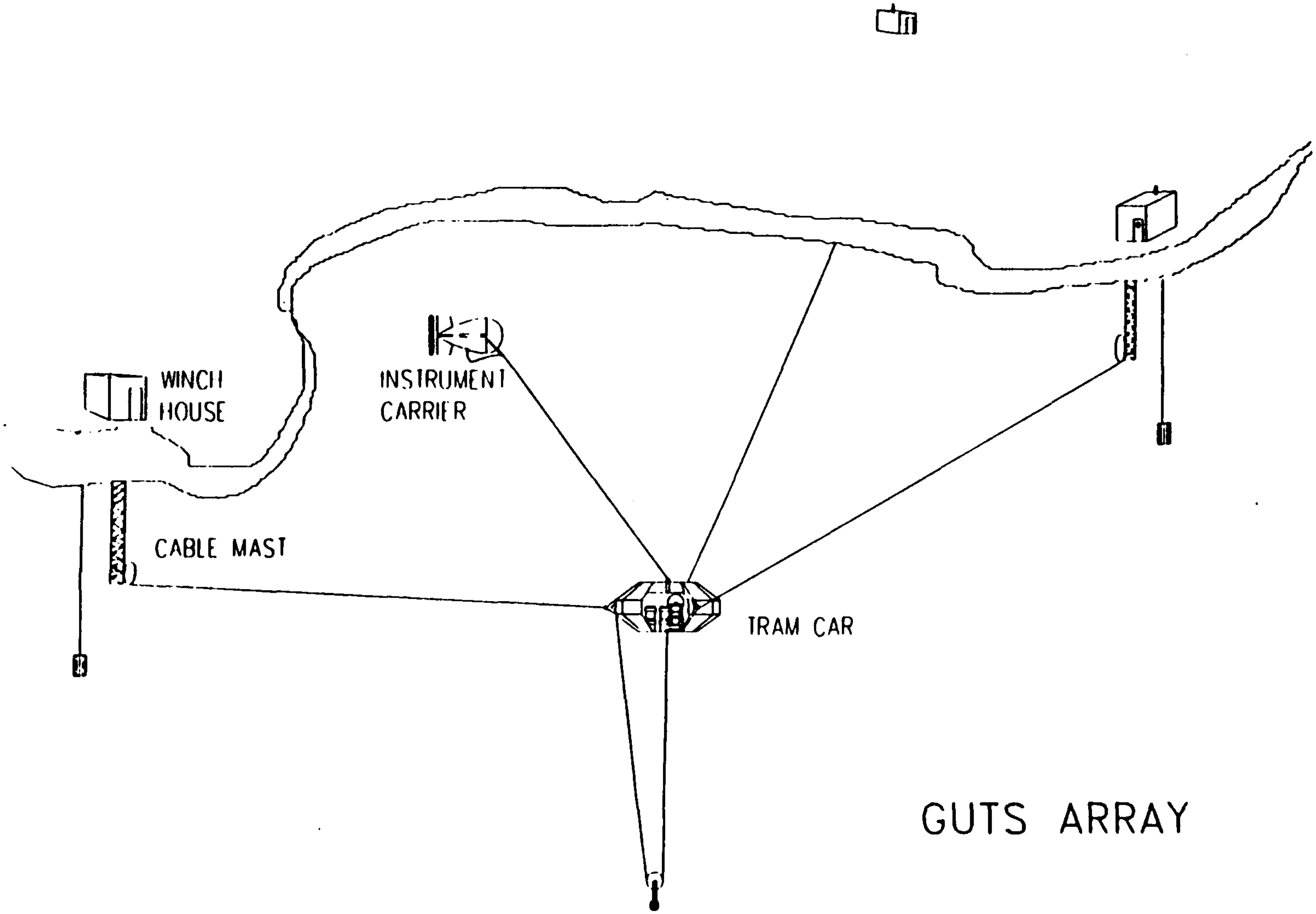


Figure 1. The Geodesic Underice Tramway System (GUTS). The major components of the array are: the instrument carrier, a counterbalance and a tram car that is a large, virtual mass supported and positioned by high tensioned cables and winches. The instrument carrier floats above the tram car; the counterbalance hangs beneath. The array will allow underice sampling over a 300 by 800 m elliptical patch with dynamical positioning of the instrument carrier to fractions of a meter.

III. ICE MECHANICS

Wilford Weeks, John Dempsey and Zednek Bazant

Although the use of GUTS technology is not particularly applicable to many aspects of the study of ice mechanics, we feel that such technology does offer several interesting opportunities worthy of exploration and development. We are particularly interested in the capability of GUTS to provide a "mesoscale" interpretation of localized ice mechanics measurements that could, in the future, lead to more regionalized extensions of detailed ice mechanics information.

SCIENTIFIC ISSUES

Brine Drainage Channels

Brine drainage channels are ubiquitous features of sea ice. However, detailed information on their spacings within sea ice of different thicknesses is not available. GUTS could be utilized to carry out detailed visual examinations of representative regions within the sampling ellipse, thereby developing information on drainage channel distributions and sizes. Such information would be particularly interesting during the spring when the ice is warming. These examinations would also provide useful information on the degree of alignment of the c-axis at the bottom of the ice, data that can be readily obtained by visual examination of platelet alignments.

Residual Stress Measurements

Mechanicians have, for some time, been concerned with possible measurement problems associated with the presence of residual stresses within floating ice sheets. The coupling of the detailed topography of the ice cover, provided via GUTS, to the top side geometry, obtainable via several different methods, would permit one to localize areas within the test area where the ice is appreciably out of isostatic equilibrium. This would allow us to localize exploratory residual stress measurements in areas where such effects are, most likely, significant.

Relationship of Surface Ice and Underice Topography

Since the early 1970's, it has been known that the topography of the lower surface of ridged areas of sea ice is significantly different from the topography of the upper surface. Current limited information supports the reasonable assumption that these differences are related to the degree of lubrication, with the ridge sail developing in a high friction environment resulting in localization, and the keel developing in a low friction environment with less localization (lower angles of repose). Detailed information on this matter is rare and would be useful in the further development of models for ridging. The coupled topography of the upper and lower sides of the test area would provide very useful information relating to such problems and to procedures for forecasting the topography of the lower surface from observations of the upper. The lower portions of all real sea ice sheets and pressure ridges are at near-melting temperatures. The lower portion of the ice sheet carries only a small part of the total forces and bending moments in the ice sheet, and contributes little to the total stiffness of the sheet, especially under long term loading. The difference in the mechanical properties between the bottom and top portions of the ice sheet needs to be understood and quantitatively determined, in order to make analytic mechanical modeling possible. It is necessary to know the thickness of the layer and how its mechanical properties vary through the sheet, in any mechanistic treatment that considers the complete thickness of such sheets. Yet because of extreme sample storage problems, particularly associated with the rapid drainage of brine from samples, there is effectively no information on sea ice under the undisturbed conditions prevailing in the lower layer. We believe that, for the testing of such ice to be successful, it must be carried out in-situ as we see no laboratory solution to these drainage problems. GUTS could be used to make measurements of the mechanical properties of this ice over a range of frequencies. We stress the importance of tests at different frequencies for the following reasons. We know that properties such as the effective elastic modulus (Eeff) are frequency dependent. Eeff can readily be determined from measurements in the acoustic range. However these are not the values that are needed for many ice mechanics problems. If frequency dependent effects can be examined, appropriate scalings can be developed to generalize the acoustic values.

Size Effects

Crack formation and propagation in ice is complicated, due to its quasi-brittle nature. Understanding the process inherently implies the need to examine cracking at a variety of scales, with concurrent knowledge of the stresses which evoke the behavior. This is because size effects make it difficult to predict fracture energy and fracture process zone size for large (Arctic) scales using small (laboratory) scale results. Study of the the deviation of the size effect from that of linear elastic fracture mechanics is needed at scales for 1 meter to 1 kilometer.

MEASUREMENTS

Acoustic tomography via GUTS could be implemented to study several areas of ice mechanics. The parameters to examine are as follows:

A-I) The flaw structure of ice sheets could be studied using tomography and crack-induced noise (development of high frequency damage assessment techniques). For instance, crack propagation experiments should be carried out at selected sites from within the GUTS array. The sites should be examined with tomography both before and after the test to see if damaged zones can be determined. In addition, during the test, crack induced noise should be monitored to determine the localization of damaged zones and the size and shape of the process zone at the fracture front. This would cover the possibility that transmission tomography may not prove adequate for damage assessment (as in the case of materials such as concrete).

A-II) The large scale fracture experiment, in which a crack of 10 to 100 m length is produced by jacking apart the opposite faces of the crack, should be accompanied by observations of the crack front and of the fracture process zone ahead of the crack front from below. Observations from this test (which features stable crack growth even with a soft loading device and closed loop control--because the load-deflection curve is always rising) should be correlated to observations from above. The location of the front, and the extent and shape of the process zone, are of major interest for the evaluation of such an experiment. These observations should be made at various fracture lengths, so that the evolution of the aforementioned characteristics would be understood (significant differences could be expected between short and long fractures).

A-III) To get information on the size effect, it is necessary to test specimens of different sizes and use a type of specimen that yields a maximum on the load-deflection diagram (and that permits achieving a stable post-peak response). The size effect is simple and easily evaluated only on the basis of the peak load values. The same measurements (acoustic, optical) could be performed on this size effect test as on the aforementioned test. It should be emphasized that the main motivation for these observations on real ice sheets in the Arctic is the difference of scale from laboratory measurements. Due to the size effect in the fracture of quasi-brittle materials such as ice, the fracture energy and thus the size of the fracture process zone are not easily predictable from laboratory experiments. Conversely, the number of experiments that can conceivably be done in the Arctic is severely limited. The specific experiments that are possible, however, are absolutely necessary to correlate the laboratory-intermediate scale data to the full-scale data. Age-old questions in this context exist concerning ice properties determined in the field versus those determined in the lab. Some effort should be made to ship ice from test sites to labs for specific tests, such as cyclic reversed testing (fatigue, elasticity, tensile strength, compressive strength and fracture). This then would allow the previous lab work to be correlated with field properties.

A-IV) The following is one example of a multi-faceted research effort: Large scale fracture experiments, in which crack lengths ranging from 1 to 100 m are produced and stable crack propagation is obtained (optimally), can be combined with tomography and residual stress measurements. The shape and size of the fracture process zone in the vicinity of the major crack tip both during the initial load-up and during the subsequent crack growth may be measured acoustically and with high-speed photography. Fracture energies can then be quantitatively related to the measured acoustic signatures. The scale of the heterogeneity is of direct interest and is incorporated in the size effect modeling. These fracture experiments would offer the opportunity to assess the scale effect from 1 m - 1 km for both full thickness fracture energy and full thickness modulus as a function of loading rate. Current evidence suggests that it is necessary to perform the above experiments over a range of temperature conditions, ranging from "cold" conditions to "warm". GUTS is able to survey the brine channel spacing and the undersurface tomography. Questions remain concerning the ability of GUTS to see the crack(s) from below and the ability to drive fully through-the-thickness cracks.

B) Tomography could be used both to further characterize and generalize the local determination of ice structure and ice property data and to provide information on the lateral variability of the internal properties of ice sheets. We stress the need here to obtain fairly detailed "ground-truth" information. To facilitate the collection of such data, the tomographic information must be processed and provided to the properties field team to guide sampling site selection. Procedures for rapidly positioning surface field parties at exact locations within the GUTS ellipse would be necessary.

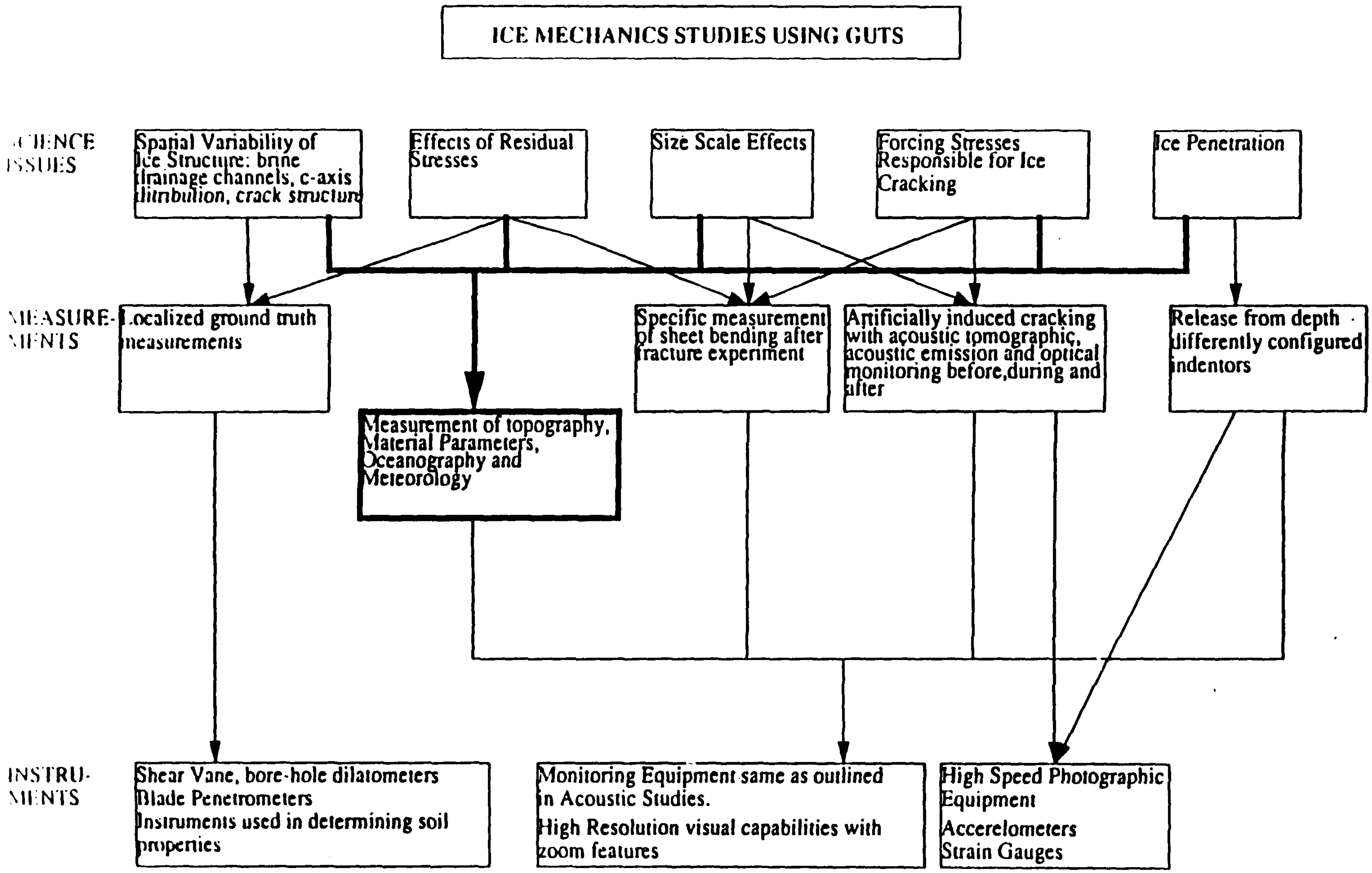
C) Residual thermal bending moments are possibly locked in the ice plates, especially after major temperature changes, and could be responsible for large-scale fracturing. Shortly after major temperature changes, it may be expected that the relief of bending moments due to the fracture experiment would lead to bending of the sheet near the fracture. This bending can be measured on the top surface, but supplementary measurements of the vertical deflection profiles from below might be useful. To distinguish between the in-plane cracks (i.e. the short thermal cracks) and the bending cracks, it would be very useful to determine the depth of the location of the acoustic sources within the thickness of plates (especially whether the source is near the top, bottom, or midthickness). To obtain some knowledge of the effect of the ice sheet thickness, the aforementioned measurements could be repeated at sites with different ice thicknesses.

D) There is considerable interest regarding the problem of a submarine surfacing through a sea ice sheet. The problem has been addressed using model tests for penetration and impact, full-scale tests, and (to a lesser extent) analytical and numerical modeling. The actual failure sequence of sea ice during an actual surfacing event has never been presented or observed. There is, moreover, currently insufficient full-scale data to verify model tests and various scaling approaches. A criticism of laboratory tests to date is that they have not reproduced the actual submarine penetration procedure and that adequate consideration has not been given to the initial state and mechanical properties of the target ice sheet: residual stress state, underice topography, temperature and salinity profile. In addition, in the context of model and large scale tests, one has natural questions regarding size and scale effects as well as isothermal "thin sheet" tests versus in situ full thickness tests. The GUTS program offers an ideal opportunity to investigate the actual failure sequence by measuring the impact and penetration behavior of released-from-depth differently configured buoyant large scale indentors. The contact pressures and deformations in the indentor and ice sheet could be measured. The GUTS vehicle would be ideally suited for accurately measuring the spatial variation in deflection of the target ice sheet. It is interesting that this one topic is underpinned by the knowledge sought in applications A,B, and C above.

TECHNIQUES AND INSTRUMENTATION

In several cases we would need the instrument package to operate either extremely close to, or in direct contact with, the bottom surface of the ice. We would also need high resolution visual capabilities with zoom features.

We are not certain of the best way to collect measurements of the mechanical properties of stable in situ ice over a range of frequencies. However, at one end of the frequency spectrum, shear vane, bore-hole dilatometers or jacks, or plate or blade penetrometer techniques could be used. We suggest that techniques for remotely determining soil properties such as developed by NASA or DOD agencies be explored to provide instrument development ideas.


ICE MECHANICS STUDIES USING GUTS
SCIENCE ISSUES
Spatial Variability of Ice Structure: brine drainage channels, c-axis distribution, crack structure
Effects of Residual Stresses
Size Scale Effects
Forcing Stresses Responsible for Ice Cracking
Ice Penetration
MEASUREMENTS
Localized ground truth measurements
Measurement of topography, Material Parameters, Oceanography and Meteorology
Specific measurement of sheet bending after fracture experiment
Artificially induced cracking with acoustic tomographic, acoustic emission and optical monitoring before, during and after
Release from depth differently configured indentors
INSTRUMENTS
Shear Vane, bore-hole dilatometers
Blade Penetrometers
Instruments used in determining soil properties
Monitoring Equipment same as outlined in Acoustic Studies.
High Resolution visual capabilities with zoom features
High Speed Photographic Equipment
Accerelometers
Strain Gauges

IV. OPTICAL STUDIES

Gary Maykut and Gary Gilbert

SCIENTIFIC ISSUES

Potential optical investigations to be made from the GUTS platform can be divided into two general categories, "passive" and "active". In "passive" studies, natural or ambient light is measured. Analyzing this data provides information on the energy balance and biological activity. "Active" optical measurements utilize artificial light sources. Active data can be used to infer information about optical properties and ice state.

Passive studies from the GUTS platform could provide input for testing and tuning radiative transfer models of the ice-ocean system. Ice thickness, temperature, snow cover, and ice algal biomass strongly impact light levels beneath the ice pack. The effects of shortwave radiation are most important during the summer melt season and in areas where the ice is thin. It would be most valuable therefore, to deploy GUTS during the late spring and summer melt season. High priority would then be given to passive mapping of the transmitted radiation field and its correlation with ice thickness and surface features. Emphasis would need to be placed on biological studies, with the identification of possible biological activity in the lower portions of the ice.

Discussions during the Electromagnetics ARI Workshop highlighted the need for much more detailed data on scattering in sea ice at both optical and microwave frequencies. Multi-year ice is known to be a highly scattering medium, complicating efforts to develop and test predictive models of radiative transfer through such ice. While available information on scattering at optical wavelengths is presently quite limited, it should be possible to obtain substantial amounts of new data by utilizing active light sources in conjunction with the GUTS platform.

If the GUTS array is deployed beneath thick multi-year ice during the spring, narrow laser beamspread measurements appear to offer the greatest potential scientific return. When possible, comparative measurements should be made using both surface and underice sources. This is because the patterns (and therefore the information content) would differ. A beam transmitted downward from the surface will immediately undergo a large degree of scattering in the snow, surface granular layer and bubbly layer above the freeboard level, thus being somewhat diffused by the time it reaches a depth of 30 or 40 cm. An upwardly directed beam will generally be much more strongly focused during passage through the lower portions of the ice. It may be possible with a suitable model to exploit differences between beamspreading in the two directions and obtain information about the vertical structure of the ice. The anisotropic nature of beam spreading and the associated energy losses are also likely to be of substantial interest within the Navy for operational reasons. As far as we can determine, there have been no simultaneous measurements of upward and downward beam spreading, even in the laboratory.

It must be stressed that in either passive or active studies, concurrent measurements of ice structure and properties would be critical in the analysis of optical data.

MEASUREMENTS

Passive Measurements

Passive mapping of the underice radiation field would be particularly valuable if the region contained thinner, first-year ice (e.g. a refrozen lead) as well as multi-year ice, or if the measurement period could be extended into late spring and summer when melt ponds become well developed. Ambient light levels beneath thick, snow-covered, multi-year ice are expected to be extremely low.

Passive optical mapping beneath the ice is of limited scientific value without complementary information on incident radiation, surface albedo, ice thickness, snow cover, vertical variations in ice structure, and amount of biogenic material. Since these quantities can vary considerably on a 1 km scale, transmission measurements must be accompanied by a detailed ice characterization and surface monitoring program.

Active Measurements

Active light sources can be located either above or below the ice, and can emit either coherent or incoherent radiation. Beneath the ice, for example, pulsed lasers and optical detectors mounted on the GUTS carrier could be used to map ice thickness or to infer information about volume scattering coefficients, biology and ice structure. Polarization measurements of light reflected from the underside of the ice could also provide information on elements in the Mueller matrix. Optical detectors on the surface could be employed to measure point spread functions (e.g. Gilbert and Schoonmaker, 1990), transmission loss and polarization changes caused by the ice.

Sources located at the surface can be used to direct radiation through the ice where it can be monitored by optical sensors on the GUTS platform. Pulsed incoherent light transmitted through the ice, for example, has been used by Trodahl and Buckley (1987) to investigate attenuation and scattering in first-year ice in the Antarctic. Results from this work confirmed that the phase function was anisotropic and that algae modified the radiance distribution beneath the ice. With regard to scattering studies, however, incoherent light does not appear to offer any particular advantages over coherent sources.

Several approaches exist which could be used to further resolve the effects of vertical variations in ice properties on light transmission. Laser beam spread measurements through ice with similar surface characteristics, but different thicknesses, could be used to infer information on scattering in the lower portions of the ice. Since most of the vertical variations in scattering occur in the snow and upper 30 - 40 cm of the ice, it should be possible to quantify near-surface layer effects by manually removing different amounts of these layers from selected portions of the floe. A less invasive procedure would be to freeze in downward-pointing fiber optics probes, which would carry laser light to different levels in the ice. GUTS sensors would then receive signals from the same source, but through ice with differing thicknesses and structural complexity. Such observations should provide a useful data base for the development and testing of layer stripping techniques that will be investigated as part of the Electromagnetics ARI. An important component in the utilization and analysis of beamspread data will be the development of improved models and inversion techniques.

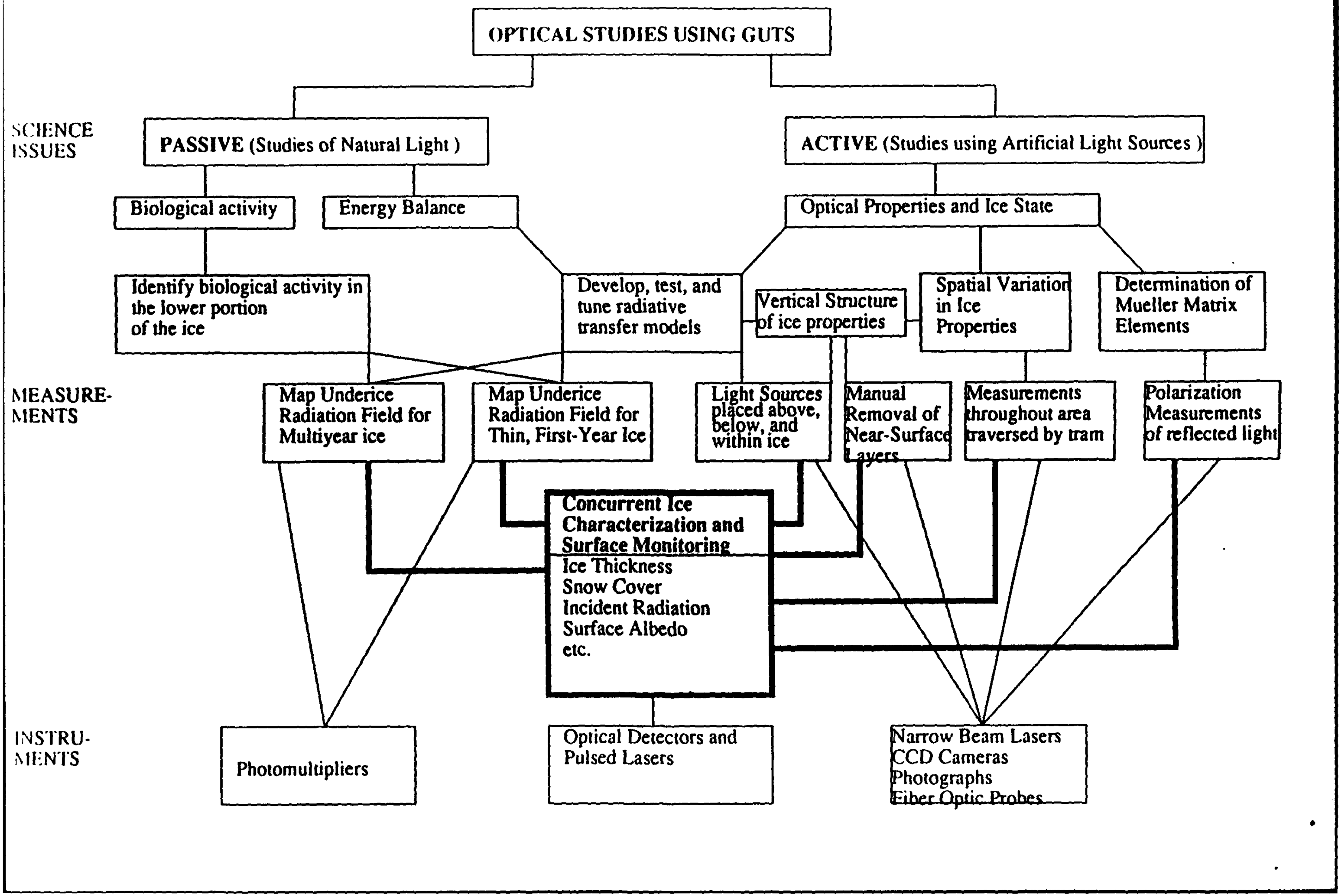
TECHNIQUES and INSTRUMENTATION

Passive Studies

Ambient light levels beneath thick, snow-covered, multi-year ice are expected to be extremely low requiring photomultipliers to resolve transmitted spectra. Suitable sensors have been developed at the Naval Underwater Systems Center, but the measurable wavelength window will be fairly narrow due to strong attenuation by the ice above 600 nm and below about 420 nm.

Active Studies

A surface-based laser with its narrow beam seems to be the best choice for the program envisioned here. Detection of the transmitted beam below the ice could be accomplished by taking photographs from the GUTS platform or by employing wide, dynamic range CCD cameras.


OPTICAL STUDIES USING GUTS
SCIENCE ISSUES
PASSIVE (Studies of Natural Light)
ACTIVE (Studies using Artificial Light Sources)
Biological activity
Energy Balance
Optical Properties and Ice State
MEASUREMENTS
Identify biological activity in the lower portion of the ice
Develop, test, and tune radiative transfer models
Vertical Structure of ice properties
Spatial Variation in Ice Properties
Determination of Mueller Matrix Elements
Map Underice Radiation Field for Multiyear ice
Map Underice Radiation Field for Thin, First-Year Ice
Light Sources placed above, below, and within ice
Manual Removal of Near-Surface Layers
Measurements throughout area traversed by tram
Polarization Measurements of reflected light
Concurrent Ice Characterization and Surface Monitoring
Ice Thickness
Snow Cover
Incident Radiation
Surface Albedo
etc.
INSTRUMENTS
Photomultipliers
Optical Detectors and Pulsed Lasers
Narrow Beam Lasers
CCD Cameras
Photographs
Fiber Optic Probes

V. ACOUSTICS

Hendrik Schmidt

The Arctic acoustic environment is characterized by very stable oceanography due to the presence of the ice cover, isolating the water from the atmosphere. The speed, attenuation, refraction and fluctuations of acoustic waves in the water are therefore reasonably well understood. A number of scientific questions remain, however, all pertaining to the presence of the ice cover. Acoustics can provide a valuable remote sensing capability for monitoring fracture mechanics and other events. The complexity of the ice cover motivates us to include the performance of acoustic inversion techniques as a scientific issue.

SCIENTIFIC ISSUES

Ice Interaction and Scattering

It is anticipated that scattering and propagation would be highly frequency-dependent. To resolve the scientific issues, experiments spanning the entire range from 10 Hz to 100 kHz are necessary on scales from kilometers down to centimeters.

The excess transmission loss observed experimentally below 100 Hz must be due to some ice interaction process. Even high attenuation in a flat ice plate does not explain the data. Ice scattering caused by roughness, keels, raftings, leads, etc. are all possible mechanisms. Recent theoretical modeling shows a strong dependence on ice keel composition, with scattering by young fluid-like keels providing the conical frequency dependence of the loss. Other experimental data has shown unexpectedly strong 3-d effects, and recent 3-d elastic models verify this behavior. A controlled, deterministic scattering experiment should be carried out to verify these theoretical models, as well as to determine the simplest description of the ice keel, which predicts the seismo-acoustic scattering, conically. The experiment should address all complicating factors, such as: inhomogeneities, anisotropy, multiple scales, mode conversion, fuzzy interfaces, and the presence of cracks and brine pockets.

At high frequencies, controlled experiments need to be carried out to better determine the primary effects that control scattering. At frequencies from 1 to 100 kHz, the resolution of parameters needed may preclude a totally deterministic comparison of models and experiment. However, to date, the environmental inputs to scattering models have been only crudely known (topography to meter horizontal scales and average material parameter values). In cases where the low resolution aspects of the environment have a primary effect (such as the highlights seen in backscattering and the general structure of the forward scattered signal), deterministic comparisons of data and models should be possible.

Long Range Propagation and Coherence

Following verification of theoretical ice scattering models at low frequencies, statistical ice property measurements combined with scattering models can be used to examine the arctic anomalies seen in long range transmission loss and coherence.

Acoustic Inversion Techniques

Two acoustic remote sensing techniques that have potential for addressing ice mechanics issues are acoustic emission and acoustic imaging. In acoustic emission, one monitors stress waves emitted by opening cracks. The emitted signal depends both temporally and spatially on the cracking parameters. Acoustic imaging is an active approach in which the medium is insonified with an acoustic source, and the received signals are inverted for environmental parameters such as crack distribution and structure. Acoustic tomography is an example of imaging and, in addition, is a technique which will be pursued in addressing the ice interaction and scattering issue above.

Ambient Noise

The relation between the large scale structure of arctic ambient noise and environmental forcing must be understood. A prerequisite is better comprehension of the mechanical behavior of ice at larger scales. Two important goals are the prediction of ambient noise from oceanography, and remote sensing of the mechanical behavior of ice on a large scale by measuring ambient noise.

MEASUREMENTS

Ice Interaction and Scattering

The parameters needed as input to 3-d propagation and scattering models are: top topography, bottom topography, thickness, material parameters vs. space and time, flaws and cracks, snow cover, oceanographic data, and meteorological data. At low frequencies the whole ice cover is interacting, while at high frequencies only the properties near the ice/water boundary are important. These parameters need to be measured to spatial scales representing a fraction of the acoustic wavelength (we use $\lambda/8$ in quoting spatial scales below) being examined.

The scattering experiments should be bistatic in nature with geometries which investigate the 3-d nature of the scattering and interaction process.

Long Range Propagation and Coherence

To proceed to long range propagation, statistical parameterizations are needed for the properties found to be important in deterministic ice interaction.

Some of the parameterizations will be important to ice mechanics work relating 1 km effects to larger scale fracture behavior. The proper parameterization may include rejection of two point statistics as a sufficient characterization. As in acoustic inversion techniques, the parameterization itself is a scientific issue.

Acoustic Inversion Techniques

acoustic emission

Since acoustic emissions propagate through ice and water, all the parameters needed for the ice interaction and scattering effort are also required in emission work to enable inversion of the source parameters associated with cracking events. In addition, to establish a relation between natural environmental forcing and ice cracking, the following environmental parameters must be determined: ice stress, ice deformation, heat flux, wind and current, and ice motion.

For controlled environmental forcing such as thermally induced cracks and those generated by artificial mechanical loading, the source parameters must be determined independently for verification of acoustic emission inversions.

To provide the maximum resolution of inversion, the acoustic emission must be recorded with dense spatial sampling, preferably in the near field, with sensors in the water as well as on the ice (e.g., hydrophone arrays). Both horizontal and vertical aperture and ice mounted arrays of 3 component geophones or accelerometers should be used.

acoustic imaging

Active acoustic imaging may provide a means for mapping ice crack structure, as well as ice material parameters needed in the ice interaction and scattering effort. Again, dense sampling is needed to obtain the high resolution (relative to the acoustic wavelength and/or crack size of interest) desired.

Ambient Noise

To enable the extrapolation of near-field acoustic emission characteristics to the large scale ambient noise environment, the following parameters must be measured: large scale ice deformation (1 - 100 km), long time scale ambient noise measurement and environmental forcing on 1 - 100 km scales (current, wind, temperature, cloud cover, waves).

The description of the parameters must be stochastic in nature.

TECHNIQUES AND INSTRUMENTATION

In this section, we restrict our discussion to techniques and instrumentation that are aimed at the deterministic examination of scales from centimeters to 1 km, and which include the GUTS platform as a tool. In order to specify techniques and instrumentation, we outline experiments addressing some of the scientific issues described above, centered around a single GUTS deployment, in an area including both smooth floes and ridge structures. Figure 2 illustrates various elements of the measurements under consideration.

We believe that the techniques and instrumentation described here should be considered as viable choices, but may not be the only possibilities. Indeed, in cases where the information obtained is essential for several scientific issues, alternatives should be viewed as a requirement. An example of this is the use of reflection tomography, which is an acoustic means of obtaining parameters of importance to both acoustic and ice mechanics issues. Reflection tomography is a viable approach, but needs further work to determine its potential. Alternatives, using optics, NMR, etc., which may measure surrogates to the parameters needed, should be solicited and vigorously pursued.

All techniques and instrumentation are followed by a parenthetical categorization on its present state of development as we know it, i.e.: (1) A STANDARD method, (2) It has been developed and used, but MODS are needed to implement it in the experiment, (3) It is VIABLE, but needs significant development, and (4) The current status is UNKNOWN. Instrumentation and

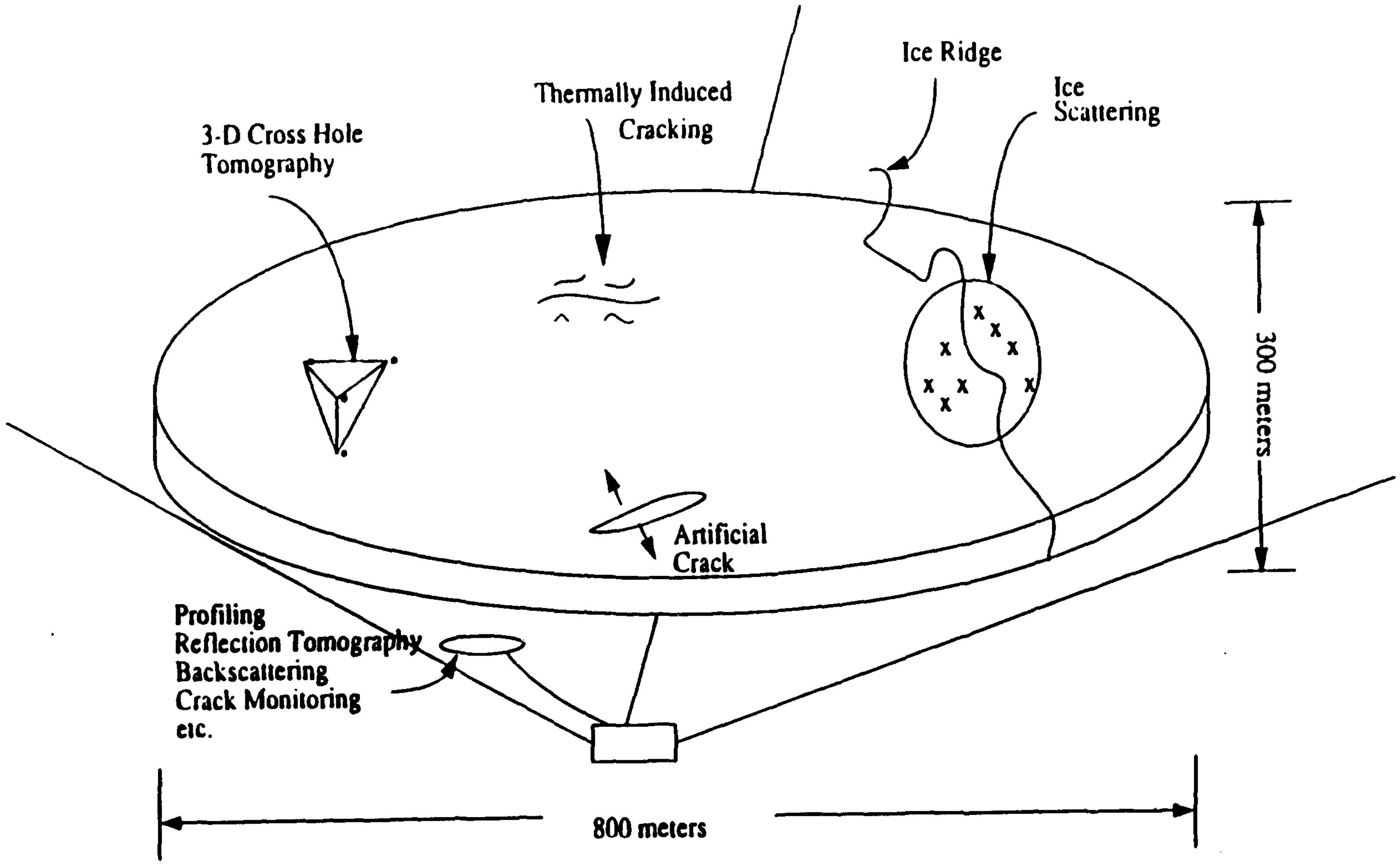


Figure 2. Elements to be measured by acoustic experiments.

techniques labeled VIABLE would require separate development programs prior to implementation in the field.

EXPERIMENT 1: Low frequency ice scattering. This experiment should be carried out in an area with a distinct, straight ice keel. The overall characteristics include frequencies of 10-1,000 Hz, spatial scales to the full capabilities of GUTS, and spatial resolution (in-water $\lambda/8$) of 20 cm.

Determination of top and bottom topography and thickness to the resolution required would incorporate the following techniques and instrumentation:

- Measurement of water level in holes. (STANDARD)
- Chirp sonar (bottom topography). (STANDARD)
- Laser scanning (bottom topography). (MODS)
- Echosounding with parabolic (1 KWatt) transducer. (MODS)
- Reflection tomography. (VIABLE)
- Source: (STANDARD)
  - 1 - 5 kHz center frequency.
  - Mobile (GUTS) to create synthetic aperture.
- Receiver: (STANDARD)
  - On the order of 10 sensors in a plane, horizontal array.
  - Mobile (GUTS) to create synthetic aperture.
- Optical thickness measurement. (UNKNOWN)

Determination of ice parameters would be carried out incorporating:

- Cores. (STANDARD)
- Bore hole tomography. (MODS)
- Reflection tomography. (VIABLE)
- Seismic wave tomography. (VIABLE)
- Source: on ice, center frequency 100 Hz. (VIABLE)
- Receivers: (STANDARD)
  - Geophones - 3 axis ice mounted.
  - Hydrophones - close to ice bottom and mobile (GUTS).
- Optical measurements of surrogates. (UNKNOWN)

Necessary oceanographic and meteorological measurements can be completed with standard techniques.

The actual scattering experiment should involve the following components:

- Sources: (MODS)
  - Omnidirectional hydrogen source, wide bandwidth (500 Hz).
  - Center frequency 200 Hz. GUTS mounted to provide synthetic aperture. (VIABLE)
  - Narrow beam, wide aperture 400 Hz source. (VIABLE)
- Receivers: (STANDARD)
  - 20 ice mounted, 3-component geophones.
  - Hydrophone array with 32 sensors in 2 vertical arrays of length 300 m and 8 individual phones in horizontal array. GUTS mounted receiver(s).

EXPERIMENT 2: High frequency ice scattering. The overall characteristics include frequencies of 1-100 kHz, maximum spatial scales driven by GUTS capabilities, and important spatial scales down to (in-water $\lambda/8$) 0.20 cm. The model/experiment comparisons would be at least in part, stochastic in nature. The measured parameters are the same as in the low frequency experiment, but the resolutions needed are much higher. The knowledge of the top topography and thickness becomes less important as the frequency is increased.

Higher resolution bottom topography would use:

- Optical Moire Fringe topography. (VIABLE)
- Source: (STANDARD)
  - Tungsten-Halogen lamp.
  - Projection grating.
  - Projection lens system.

  Receiver: (STANDARD)
  - Reference grating
  - Receiving optics
  - CCD camera
- Acoustic back propagation. (VIABLE)
- Frequency: 10 kHz < f < 100 kHz to be determined via simulation (VIABLE)
  and positioning constraints of GUTS platform.
- Source: STANDARD)
  - GUTS mounted.
- Receivers: (STANDARD)
  - GUTS mounted to obtain scattered field. (VIABLE)
  - GUTS mounted - Differential arrangement to get derivative of the scattered field.

The knowledge of the ice parameters in the lower portion of the ice would be obtained via:

- Acoustic back propagation. (VIABLE)

The scattering experiments should involve:

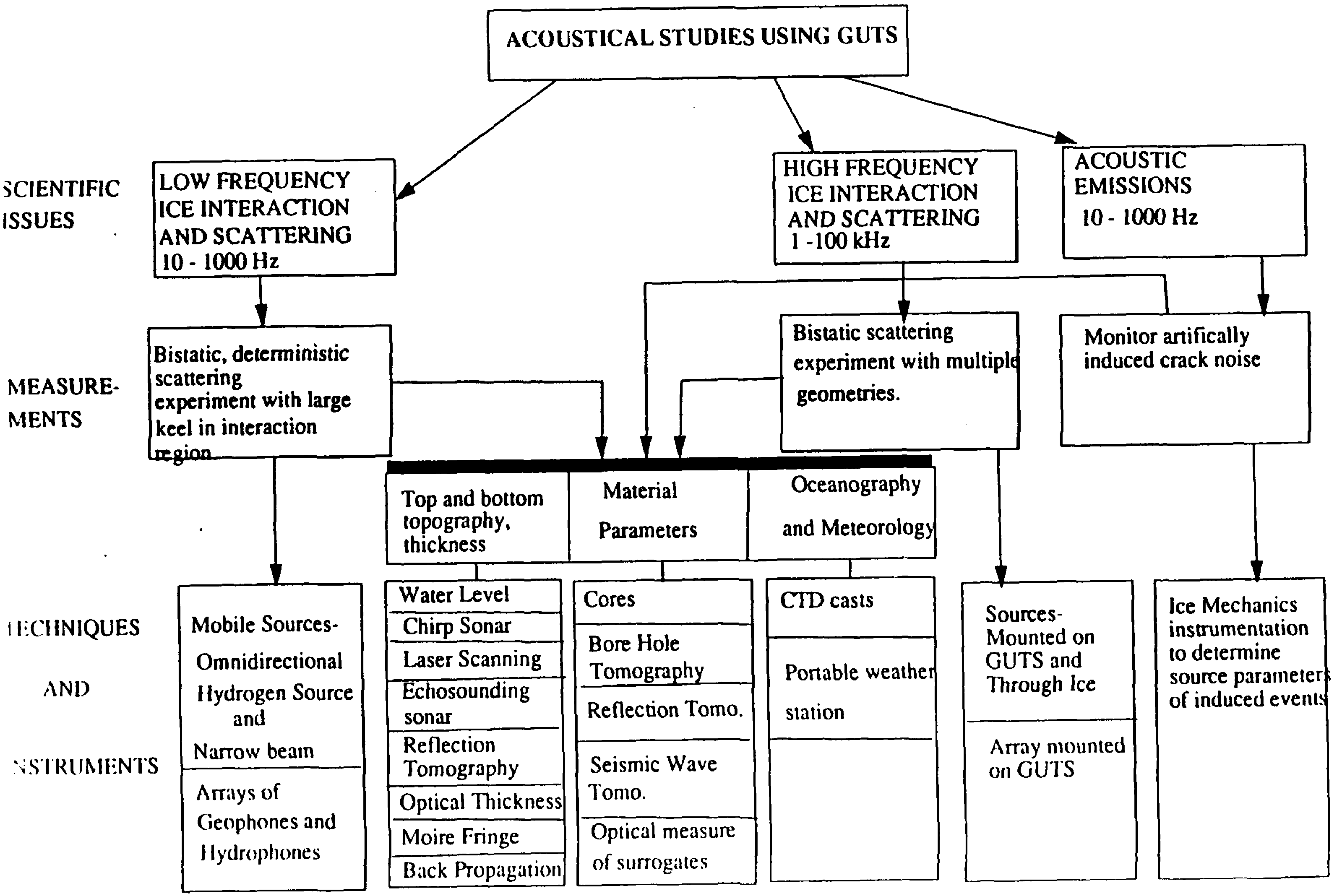
- Sources: (STANDARD)
  - GUTS mounted for backscattering.
  - Stationary, mounted from ice for bistatic measurements. (STANDARD)
- Receivers: (STANDARD)
  - GUTS mounted.

Multiple geometries are important in these experiments due to the probability of stochastic model/experiment comparisons.

EXPERIMENT 3: Acoustic emission from artificially induced cracks. The overall characteristics include frequencies of 10-1,000 Hz and spatial scales on the order of 100 m. Spatial resolution is the same as in Experiment 1 above. The input parameters needed include those of Experiment 1, with the addition of source parameter determination via instrumentation discussed in the ice mechanics section.

Site selection of the bore hole tomography instrumentation should be made so that an induced thermal cracking acoustic emission experiment can be carried out within the volume it is sampling.

Reflection tomography should be carried out if region cracking is induced before and after the acoustic emission experiments.


ACOUSTICAL STUDIES USING GUTS
SCIENTIFIC ISSUES
LOW FREQUENCY ICE INTERACTION AND SCATTERING 10 - 1000 Hz
HIGH FREQUENCY ICE INTERACTION AND SCATTERING 1 -100 kHz
ACOUSTIC EMISSIONS 10 - 1000 Hz
MEASURE-MENTS
Bistatic, deterministic scattering experiment with large keel in interaction region
Bistatic scattering experiment with multiple geometries.
Monitor artifically induced crack noise
Top and bottom topography, thickness
Material Parameters
Oceanography and Meteorology
TECHNIQUES AND INSTRUMENTS
Mobile Sources- Omnidirectional Hydrogen Source and Narrow beam
Arrays of Geophones and Hydrophones
Water Level
Chirp Sonar
Laser Scanning
Echosounding sonar
Reflection Tomography
Optical Thickness
Moire Fringe
Back Propagation
Cores
Bore Hole Tomography
Reflection Tomo.
Seismic Wave Tomo.
Optical measure of surrogates
CTD casts
Portable weather station
Sources- Mounted on GUTS and Through Ice
Array mounted on GUTS
Ice Mechanics instrumentation to determine source parameters of induced events

VI. Boundary Layer Oceanography

Tim Stanton

The rapid spatial measurement of properties under a well-mapped ice flow provides a unique opportunity to rigorously relate the turbulent flux field in the oceanic boundary layer to topographic features.

A set of existing measurement systems can be readily carried by the GUTS instrument platform to address scientific issues.

Scientific Issues

-What is the spatial structure of turbulence in the boundary layer under sea ice? How is it related to temporal measurements at fixed sites?

-How is the turbulent flux field and dissipation rate related spatially to the sub-ice topography?

-Can the form drag and effective roughness scales be quantified from a wide sampling of fine scale topography and simultaneous stress estimates?

-Is there evidence of ice-pumping, i.e., enhanced melting of ice keels and the resulting transport of super-cooled, saltier water in the lee of ice keels?

-Can the stresses in the vicinity of a specific strong topographic feature (measured from a rapid sub-ice stress mapping) be compared directly with concurrent ice strain measurements over a range of current forcing magnitudes and directions?

-How is the upper pycnocline affected by the sub-ice topography? In shallow pycnoclines, is there evidence of internal wave generation (and enhanced stresses) near severe sub-ice topography? Does this enhance down-stream entrainment?

MEASUREMENTS

It would be desirable to measure the horizontal and vertical fields of u', v', w', T', S', and ρ' on a 1 km horizontal scale through the surface mixed layer and upper pycnocline. Measurements should be made across the entire turbulent spectrum to dissipation (sub cm) scales, including χ and ε.

The initial sampling strategy is to complete a survey of the turbulent quantities across the entire under-ice area, along with a complete characterization of under-ice morphology. This should be tied to concurrent boundary layer measurements at a fixed location, plus rapid horizontal transects of mean and turbulent scale quantities.

After the initial mapping, flow across specific pressure ridge keels could be studied in detail. This would address a number of scientific issues including pumping, mixed layer turbulence enhancement, internal wave generation and drag.

Measurements to be taken include:

A. Survey Spatial Measurements

-CTD (high accuracy, moderate resolution).

-C', T', u', v' and w' in four levels, extending 6 m in the vertical (10 cm resolution).

-C', T' (to mm scales), and sub-meter scale shear to estimate χ and ε, the temperature and kinetic energy dissipation rates.

-High resolution imagery of the sub-ice topography and morphology, including optical ranging and sizing of features.

-1 m resolution, current profiles to 50 m depth, with approximately 10 m horizontal resolution.

B. Rapid Spatial Measurement

-Measurement of mean and turbulent quantities as a function of x,y, made as synoptically as possible. Typically, these transect measurements could be made at a speed of at least an order of magnitude greater than the mean current.

TECHNIQUES and INSTRUMENTATION

Existing instrumentation is available to measure the variables specified above. The survey, rapid survey and temporal measurement system will be described separately.

Spatial Survey

The following instruments could be deployed on the GUTS instrument carrier (IC). The IC should move at between 20 and 50 cm/s at depths between 5 and 10 m below the ice in the survey mode.

1. A pumped Sea Bird CTD and a 6 m, 4 cluster turbulence frame deployed down from the front of the IC (150 watts, 110 volts, 1 video channel for a 50 KHZ data carrier). The IC platform motion and vibration spectrum need to be quantified. This sensor requires a velocity variance of less than 1 cm/s^2 at frequencies greater than 0.5 HZ.

2. The 3 beam, 5 MHz acoustic doppler system and microstructure T and C sensors in the DAMP package estimate χ and ε (20 watts, 12 volts, 1 video channel for a 2.5 m baud bi-phase data stream). The 1.2 m long, 12 cm diameter package must have a clear forward view of the flow with a minimal flow distortion (with similar vibration requirements as in 1).

3. An intensified, high resolution, narrow band camera mounted near the end of the IC could be paired with a 532 nm scanned laser to obtain quantitative imagery of the sub-ice surface. (120 watts, 110 volts, 1200 baud 2-way RS232 coms to both the camera and laser package.) The laser package is 1.3 m by 30 cm in diameter, and must be near the front of the vehicle to provide a maximum baseline between the camera and laser port.

4. A five beam 600 KHz, downward-looking, broadband ADCP could be used to define larger scale shear and to navigate the turbulent velocity measurements (1 and 2 above). The new

broadband technology permits higher spatial and temporal resolution than conventional incoherent ADCP systems.

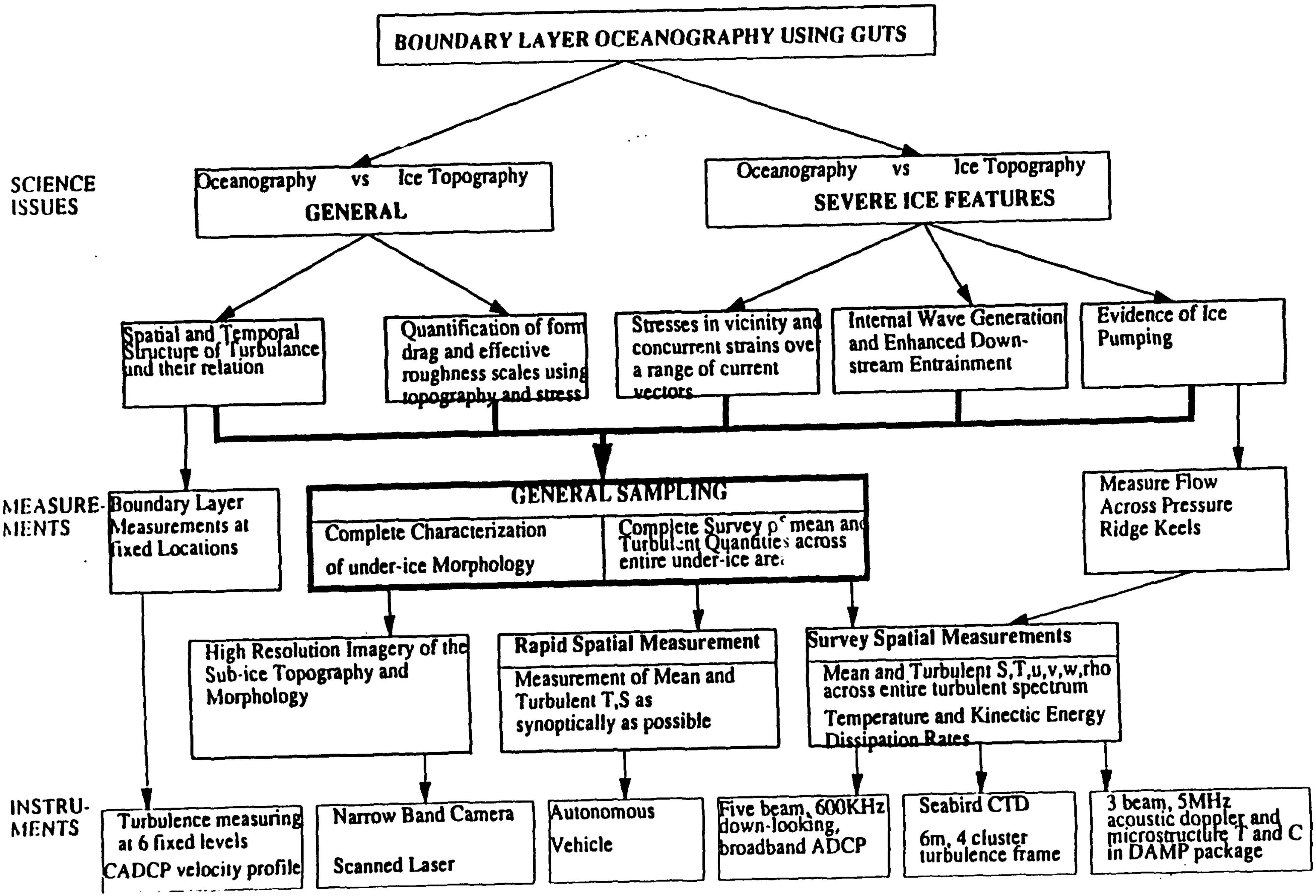
Rapid Spatial Sampling

Autonomous vehicles could be used to obtain rapid spatial measurement of T, S, T', and S' in parallel with the survey and time series measurements. The velocity of the vehicles should be about 2 m/s, nearly an order of magnitude greater than typical storm induced current velocities. These could provide a nearly "snapshot" view of T, S, T', and S'. These measurements place no interface requirements on GUTS, but require the use of ranging and surface support equipment used in the GUTS deployment.

Static (Time-Series) Measurements

Turbulence measuring clustering (u,v,w,t,c) at 6 fixed levels in a central location.

Bistatic CADCP velocity profile u,v,w, with a 10 cm vertical resolution to 30 m.


BOUNDARY LAYER OCEANOGRAPHY USING GUTS
SCIENCE ISSUES
Oceanography vs Ice Topography
GENERAL
Oceanography vs Ice Topography
SEVERE ICE FEATURES
Spatial and Temporal Structure of Turbulance and their relation
Quantification of form drag and effective roughness scales using topography and stress
Stresses in vicinity and concurrent strains over a range of current vectors
Internal Wave Generation and Enhanced Down-stream Entrainment
Evidence of Ice Pumping
MEASURE-MENTS
Boundary Layer Measurements at fixed Locations
GENERAL SAMPLING
Complete Characterization of under-ice Morphology
Complete Survey of mean and Turbulent Quantities across entire under-ice area
Measure Flow Across Pressure Ridge Keels
High Resolution Imagery of the Sub-ice Topography and Morphology
Rapid Spatial Measurement
Measurement of Mean and Turbulent T,S as synoptically as possible
Survey Spatial Measurements
Mean and Turbulent S,T,u,v,w,rho across entire turbulent spectrum
Temperature and Kinectic Energy Dissipation Rates
INSTRU-MENTS
Turbulence measuring at 6 fixed levels
CADCP velocity profile
Narrow Band Camera
Scanned Laser
Autonomous
Vehicle
Five beam, 600KHz down-looking, broadband ADCP
Seabird CTD
6m, 4 cluster turbulence frame
3 beam, 5MHz acoustic doppler and microstructure T and C in DAMP package

VII. ENGINEERING

LeRoy Olson

The GUTS system is shown in Figure 1. The underice study area is a 300 m by 800 m ellipse. Two of the cable winches will be located 1.6 km apart. The third cable winch (the master), which controls the signal and power cable, will be located 1 km, equidistant from the other two. The control winches have enough power to move the tram car at a uniform speed of .5 m/s. (The sizes and weights of GUTS components are constrained by weight limits that can be hauled by Twin Otter airplanes.) The tram car will travel 30 meters below the bottom of the ice, with the instrument carrier located at any chosen depth between the tram car and the ice bottom, but nominally about 2 m below the ice. The conceptual design of the instrument carrier has a payload for scientific instruments of 150 pounds. Initial tests should be conducted under relatively flat ice about 10 m thick. Ultimately, the system will be required to operate under moderate depth keels with the control winches installed on more uniform ice to either side. The thinner ice of refrozen leads should not be a problem for deployment, but there is certainly a greater danger of shearing or separation of the lead; motions much greater than 100 m would require re-deploying the equipment. The apparatus is being designed to be deployed during spring ice conditions. Deploying the system should take four people 5-6 days, and recovery should take several days. Once the apparatus is operational, two people will be able to run the system until recovery time.

We judge the above capabilities to be adequate for most of the scientific experiments discussed at the workshop. Once the basic system is deployed and tested, other design modifications for specialized studies can be included. For operating across leads, a much simpler two-dimensional system could be deployed using GUTS components. This approach for such studies across open or refrozen leads should be examined.

It was strongly indicated that a need exists for optical data storage at the computer site to accommodate large data sets. Of the four fiber optic leads in the signal cable, two will be spares which could be used for full bandwidth data transmission to optical recorders in the future. This feature will not be utilized in the initial GUTS deployment unless individual researchers provide the necessary equipment. In the current GUTS design, the limiting factor in data transmission is the rate at which the MassComp computer can accept data. In the future, upgrades could include enhanced computing capability.