HYDRAULICS DIVISION

Technical Note

DATE: September, 1982 **REPORT NO:** E82-06

TITLE: A Note On Instrumentation Techniques for the Measurement of River Ice Thickness and Certain Related Parameters

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REASON FOR REPORT: A Provincial/Regional enquiry to NWRI as to whether an instrument existed, or could be readily developed, to measure the thickness of river ice by indirect means, without the necessity of physically drilling holes in the ice-cover.

CORRESPONDENCE FILE NO: Study 82-376
Study 82-377

1.0 INTRODUCTION AND BACKGROUND

This note summarizes work recently performed at CCIW in reviewing the current state-of-the-art in "non-destructive/non-penetrating" sensing of river ice-thickness using modern instrumentation methods.

The immediate stimulus for this work was a Provincial and Regional enquiry as to whether an instrument existed, or could be readily developed, which could measure the thickness of river-ice by "remote sensing" or other indirect means.....without the necessity of physically drilling holes through the ice cover.

The nearterm goals of this project, and the various terms-of-reference and constraints impacting upon it, are presented early in the discussion.

This investigation into ice thickness metrology, which was initially quite wide-ranging, eventually zeroed in on three or four instrumentation approaches.....each of which has been implemented somewhere before, at least to some degree. One of these approaches used electromagnetic (radar) propagation; two were acoustic; one used electromagnetic subsurface induction.

This note concludes with what is considered to be, given the fairly-complex circumstances pertaining to this technical field, the most appropriate recommendation for future action by NWRI and MOE New Brunswick.

It should probably also be mentioned that this is not an instrumentation-design report.....measurement methods are reviewed but not specific instrument details. Likewise, recommendations for action center on methodologies.....but at this stage are not specific task-lists or detailed contractual statements-of-work.

2.0 GOALS

The final goal of this instrumentation activity was to be the successful demonstration, in the region in question, of an ice-thickness measuring instrument, which would clearly provide superiority-of-operational-performance compared to the traditional methods used previously.

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More specifically, the performance goal, or objective for such ice-thickness instrumentation, was agreed to consist of the following key capabilities:

- measure river ice thickness accurate to 3 cm or better
- display and record ice-thickness continuously
- weigh less than 50 lb for portability
- be fully cold-weather-compatible
- be conveniently useable by a WSC field-technician

(Appendix 1, extracted from the relevant minutes, provides more detail on some of these objectives.)

In addition to its primary function of measuring ice thickness, it was considered a valuable supplement if any such instrument could measure or display two other related parameters:

- thickness of any snow layers upon the ice sheet
- thickness of any frazil ice accumulations under the ice sheet.

(Equivalently, any such instrument should not be confused, or give erroneous readings, due to the presence of either of these two frequently encountered conditions.)

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Although the above was the final goal, there were clearly a number of subsidiary goals, or milestones, which would be achieved during the process of attaining this final goal. At present, these intermediate goals are seen to be the following:

Firstly, to more thoroughly explore and review previous work, some though not all of which was previously known. The general field of ice measurement is one that has been active for many decades, though not strongly at CCIW. This review would, it was anticipated, encompass several different known instrumentation technologies for measuring ice indirectly.

Secondly, following such review, to prepare a recommendation for the best course of action, bearing in mind the various project constraints and terms of references (see the next section). To present such recommendations to NWRI and MOE, New Brunswick, for their review and endorsement. Also, at this stage, funding would have to be sought.

The third, intermediate objective would be to put into effect whatever procurement or contract action was required to obtain or create the selected instrument. If a commercially-available instrument had been identified and recommended, this action would be a straightforward procurement. If a satisfactory off-the-shelf instrument did not exist, but a promising technology had been identified, then some contract action involving custom engineering by a specialist supplier would be more likely.

As soon as such instrument was delivered and received, the final objective of demonstrating and evaluating it under realistic winter field conditions would shortly follow.

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This present note is intended to fulfil the first and second objectives stated above.

3.0 TERMS-OF-REFERENCE AND APPLICABLE CONSTRAINTS

Impacting on this work were a number of non-technical factors and circumstances which deserve mention at this stage, before presentation of the technical discussion.

The first point is that development of new hardware was not anticipated, at least in the first approaches to this work. Rather the intent was to see first what could be achieved or demonstrated with existing instrumentation. That is, the use of commercially available off-the-shelf equipment was the preferable approach, if possible.

Second, the simplicity of the "standard" method had obvious implications. The conventional technique for ice-thickness measurement was that of simply drilling narrow holes through the ice cover, and physically measuring ice thickness with a simple and cheap rod or tape scale. (Frazil can also be detected with a collapsible pseudo-umbrella.) Both these ice tools are very low priced. Thus there is a certain natural caution and constraint against any multi-$K instrumentation proposition which merely offers comparable performance. There should be very significant data acquisition and/or operational advantages, before substantial commitment is made to any more complex method.

Third, should it happen that no readily-available, portable, winter-worthy, "ice-meter" existed, then variants of existing equipment should be considered as the next possibility. Developments from scratch were neither desired nor anticipated. This also ruled out, at least in the early phases, new ideas, results from "brainstorming sessions", or innovative concepts involving research.....even though some appeared plausible. Such subject matter is not included in this present document.

Fourth, although the original stimulus came from staff in one particular Region, and related to one particular river, it was clear that potential for general, National, application in Canada's rivers (and lakes) existed. Thus conditions which were site-specific should not become too limiting or controlling.

Fifth, as with many reviews of instrumentation technology, the technological data base not only on the particular specialty in question (measurement of river ice thickness), but also certain related and possibly relevant technologies should be examined, in case technically promising approaches had evolved therein. These other fields will be mentioned in the technical discussion where appropriate.

4.0 MEASUREMENT SCENARIO AND LOGISTICS

The operational situation of major importance is shown in sketches 4.1a, 4.1b. This case is also the simplest. There is a river with solid ice-cover.....i.e., an orderly layer of freshwater ice, with water beneath.....the objective being ice thickness measurement. (To a quoted target accuracy of 3 cm......or better if possible.) And the preferred and expected field logistics arrangement is by snowmobile; so any instrumentation has to be snowmobile compatible, allowing tens of kilometres of transits per day.

Several variants of this simple operational scenario exist, almost by definition.

The first is that shown in 4.1c, where the simple ice cover has superimposed snow or slush, and/or underlying frazil-ice crystals or aggregations in the water beneath the ice layer. It would be a very desirable supplement if these other two layers could be simultaneously measured or estimated or displayed by whatever device measures ice thickness.

Another variant is the case of thinner or melting ice cover of marginal safety. Use of an all-terrain (buoyant) vehicle is not necessarily excluded for ice-measurement work.

A major extension are the cases of partial ice cover, with moving ice floes (Figure 4.1d), or of ice jams (Figure 4.1e). Because the river surface is then inherently unsafe, any measurement has to be from above (helicopter-based?) or from beneath the water surface. Again estimating the ice thickness, (or topography) in these two cases is another desirable supplementary objective.

It is recognized that, in the limit, if the river-ice and its superimposed snow-cover has gone through a series of freeze/thaw cycles, then a very complex multilayer situation may exist.....almost certainly beyond the capabilities of any small portable instrument to resolve.

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Against this general "field scenario", the instrumentation/operational combinations which eventually received most attention are:-

- sledborne (snowmobile-pulled) "ice-radar" transmitting electromagnetic impulses vertically down through the ice.
- Ultrasonic probe or thickness gauge physically applied to the top ice surface.
- Inverted acoustic echo-sounder transmitting acoustic pulses upwards from the riverbed.
- A fourth possibility based on induced-current/bulk-resistivity effects exists and is also discussed. It too would be a sled-mounted, snowmobile-pulled, arrangement.

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The pro's and con's of these four possible methods (each of which exists and has been demonstrated.....at least in part) are discussed in the next four sections.

5.0 ELECTROMAGNETIC SUBSURFACE-PROFILING THROUGH ICE, USING IMPULSE-RADAR

- This technique is effectively radar-echo-ranging over extremely short ranges, whereby directional radar signals are transmitted vertically downwards through the ice/snow/water layers, and the reflected echoes detected and displayed.
- In general, with plane-wave electromagnetic propagation, there will be reflected energy (i.e., "echoes") whenever signals pass between layers of different electromagnetic-impedance. In the ice/snow/water situation, these reflections occur whenever the dielectric-constant, or the dielectric-loss-factor, changes in the layered media. Figure 5.1 shows a typical experimental "ice-thickness radar-system" of the mid-seventies.
- Within certain conditions, this radar method can produce satisfactory, high-resolution signals and data, as several investigators have found, and as theory predicts.
- Much work in applying this radar technology has been done over the years. At least 12 groups have been active in radar ice-thickness measurement. (See Refs.) More effort has been applied to sea ice than freshwater ice.
- An astonishingly wide variety of "impulse radars" has been created and applied to ice thickness profiling by various research groups. For example, in the matter of radar wavelength/frequency, instruments have been made using X-band, S-band, L-band, UHF, and/or VHF; (i.e., wavelengths from 3 cm to 3 metres). Again, in respect of the actual electromagnetic pulseshape transmitted, different radars have featured.....pulsed-CW; CW/FM; "mono-cycle"; "synthetic pulse"; "pseudo-random MSK"; etc. So comparing one resulting data set against another requires care.
- In nearly all this work there has been a general and surprising dearth of radar-engineering-type calculations and predictions of expected signal amplitudes. Most of such work appears experimentalist in approach. However, theory is definitely difficult, as any text on electromagnetic propagation in layered media will indicate.

- o Physically any such instrument would eventually consist of a portable box; a microwave cable; and a hopefully-small antenna. [However, previous experimental equipment was bulky.....as it used standard items. Figure 5.1 is typical].
- o The most critical instrumentation technology involved is that of sending and detecting ultra-fast pulses (nanoseconds). This is hundreds-of-times faster than conventional radar applications.
- o Some closely related fields of application from which at least some of this ice-radar work derives or relates include.....a) E.M. subsurface probing for geophysics, b) Time-domain reflectometry along wires or transmission lines, c) E.M. subsurface probing for military ordnance purposes, d) Glacier radio echo-sounding.
- o Detectable radar reflections also occur off snow layers. This can be either useful, or a problem. (Ref. A22)
- o The main technical areas of high challenge in this "ice-radar" field are a) displaying nanosecond pulses on paper b) antenna broadband directivity, c) antenna motion compensation, d) fundamental choice of waveform, as previously mentioned.
- o In respect of high-resolution microwave radar (3 cm wavelength) the IWD/CRC work of 74/75 has not been bettered and is still valid. (Refs. A4, A13, A14)
- o Of interest, DOT has a major ($0.5M) project underway since 1977 with Canadian Industry, to develop a "sea-ice thickness sensor" using radar methods. However, interest here is in ice several metres thick. Our resolution requirements are much more stringent as the measurement range of interest is from about 10 to 100 cm. (Ref. A20)
- o Presentation to a field operator could be either signal (y)-versus-time/depth (x) probably for stationary (spot) measurements, or "echogram" type of format, with signal producing marking intensity and the chart showing profile of ice depth as the radar moved across the ice. Each has been frequently used.
- o The reflected signal situation for microwave radars would in good conditions be as sketched in Fig. 5.2A, with good reflections off the upper ice surface and lower ice surface. Useable reflections (up to 10%) would also appear off snowlayers (Fig. 5.2B). However.....

- If water is present, or slush, or wet snow, the performance degrades markedly due a) to greater initial reflection at the first interface (Σ'= 81), plus b) additional absorption of signals in the liquid water. That is, first reflection off the first "wet" surface goes to 90% and reflection off the ice bottom virtually vanishes.
- Figure 5.3 gives best perspective on this important factor and trade-off parameter. This shows clearly that at the short radar wavelengths (3cm/X-band/10 GHz) needed for good thickness resolution, the signal absorption, if water is present, is enormous. (3000db/metre = 3 db/mm of water.) There are also additional losses due to increased surface reflections.

  Viewed alternatively, in the VHF/UHF band (say 300 MHz) the attenuation loss in water is tolerable, but the related wavelength of one metre (in air....though less in ice and water) prevents good thickness resolution.

  However, it is correct to note (as will be later enlarged upon) that short wavelengths give short penetration at high resolution, relatively long wavelengths give deep penetration at low resolution. This is, in fact, effectively the electromagnetic "skin-depth" phenomenon.
- Radar signal strength in ice more generally varies as a function of:- ice temperature/scatterers/crystal shape/ionic concentration/water content/frequency/resonances. As stated, water content is the most bothersome.
- The picture is not so negative if one notes that broadband radars can transmit pulses at many different wavelengths simultaneously. Thus for resolving thin ice, the short microwave components may well penetrate sufficiently (tens of cm), whilst for frazil accumulations much thicker than the ice the longer VHF/UHF components should (and reportedly do) penetrate sufficiently to delineate frazil boundaries. Note though, that broadband radar instrumentation is complex, and amongst dozens of ice-radar papers only one could be claimed as a quality technical presentation re a broadband unit.

  The picture is also not so negative if one assumes cold, dry conditions.....with no melting.....as exists widely in Canada in winter.

- As a common comment for each of the four techniques discussed, it was noticeable that much conflicting evidence is encountered or reported concerning data quality from different radar-equipments and experiments.
- At least two Canadian companies have capability in this specialist "ice-radar" technology, as do two universities. There is also experience in several government departments.....predominantly CRC/DOC.

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- These various pro's and con's can be summarized as follows:- a) In respect of freshwater ice-thickness-measurement (in the range 10 to 100 cm, say) assuming that the ice is cold and dry, then microwave impulse radar (of the simpler single-frequency/single-wavelength type) can readily obtain good-definition, useable, reflections from upper and lower ice surfaces, allowing ice thickness to be measured by such "remote sensing". (Canada's work in 74/76 timeframe in this area has not been bettered). However, as soon as several mm of water are present, either lying on the ice, or wetting any snowlayer present, the reflected centimetric radar signals become significantly degraded due to attenuation of the high frequency/short wavelength spectral-components (as per Figure 5.3).

  And of course the centrimetric signal penetration into the water-laden frazil zone under the ice is effectively zero.

  b) In respect of underice frazil-accumulation measurement (in the thickness range 50 to 500 cm, say) then UHF/VHF impulse radar can reportedly detect reflections from the frazil/water interface and hence estimate frazil accumulation. (No such work in Canada to date). However, the relatively long wavelengths needed to achieve signal penetration into the water/frazil mixture prevent good resolution of the close-spaced ice layer reflections.

  c) This, by itself, neither short (centrimetric) wavelength radar, nor longer (decimetric) wavelength radar, offers a fully satisfactory solution. However, use of a multiple-wavelength radar (conventionally termed "broadband") offers promise of being much more generally useful.....and there is considerable evidence to this effect in the References.

However, it should also be pointed out that any radar instrument tends to be fairly complex and expensive, and broadband versions more so.

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These are the major pro-and-con factors governing ice-radar usage.

6.0 ULTRASONIC THICKNESS GAUGING DOWNWARDS THROUGH THE ICE

- Technologically this method is virtually identical to ultrasonic thickness-gauging (or flaw detection) as used in industrial NDT (non-destructive testing) work. A small acoustic probe is applied to a metal block (or other solid), a pulsed compressive-wave transmission sent out, and a clean reflection or echo obtained from the opposite wall or surface. In our case, the solid plate would be the ice-sheet.
- Reflected signal situation would be as sketched in Fig. 6.1.....a substantial reflection at the ice bottom (with some expected internal scattering and shear wave-reverberations as well). There could also be several acoustic multiples.
- This method should be able to produce satisfactory, high resolution presentations.....in certain conditions. (As has been found, and as theory predicts.) Though there has been a noticeable dearth of sustained effort applied to this technology in connection with ice-measurement.
- Figure 6.2 shows a typical commercial sonic thickness gauge.
- For this application one possible eventual instrument configuration would be as per sketch 6.3.....with points of similarity to a walking stick. (Push end on ice/pull trigger/read display.) Of course, this is not continuous sensing of ice-thickness; it is spot measuring. Vehicle must stop each time. But it is far quicker than hole-drilling.
- A second possible configuration (based on that routinely used in continuous flow-line manufacturing) would be as per sketch 6.4.....,

based on using ultrasonic wheel-transducers. This would give a continuous echogram-type profile on chart paper. [Recognized, however, are some non-trivial aspects such as snow-removal, though different remedies can be conceived.]

- Nevertheless, the recognized area of major difficulty is making good coupling to the ice, to transmit vibrations. [Oil coupling film often used.]
- Because of limited directionality, useful good quality signals from the underlying frazil are not expected as there would be simultaneous internal acoustic multiples.
- It is noteworthy that this acoustic approach is in one respect complementary to the impulse-radar approach. The radar probe works best in dry, cold conditions and degrades when slush or meltwater appears. The ultrasonic probe works best in wet conditions with water present, and probably becomes more difficult in very cold, dry, powdery, conditions.
- Accuracy and resolution is expected to be considerably be better with this approach......largely because the acoustic wavelength would be many times shorter than with radar. Accuracy should be limited mainly by the precision of known sound-speed in the ice-type of interest.....and pre-calibration may also be possible. Resolution should be a function of the narrow pulse-width used.
- At least one competent Canadian company is active in this technology. No major problems are anticipated in obtaining hardware for feasibility demonstration.

7.0 ACOUSTIC PROBING UPWARDS FROM BENEATH THE ICE-COVER (Bottomside or Inverted Echo-sounding)

- Virtually by definition, this method is effectively the functional inverse of the previous technique. It is frequently termed bottomside, as opposed to topside, echo-sounding. It would involve an acoustic transmitter/receiver located on, or close to, the river bed, sending directional pulses upwards to the ice sheet, and detecting and displaying the resulting acoustic reflections.

- This method has potential for producing satisfactory high resolution presentations....in fact probably the best overall data-quality of the several methods reviewed in this report. This is one of its two major advantages.
- One embodiment of this method is shown in Figure 7.1. The acoustic transceiver is on or at the river bed, and either the moving ice and frazil flows past it, or the transceiver is moved if the ice cover is fixed. It should straightway be stated, of course, that this submerged requirement is the major disadvantage, though needed to achieve the associated best-of-all data presentation.
- This method <u>can</u> display both the ice-thickness and the accumulations of frazil-ice in the water. The echo signals from frazil (both particulate and aggregate), the reflected signals from the ice under-surface, and the reflected signals from the ice top-surface are expected to be the clearest of the several methods reviewed. (Typical signal strength might be 10% reflection (frazil); 50% from under-surface, 20% from upper-surface.....in idealized conditions of course).
- Most of the relevant work on acoustic bottom-side sounding of ice has been done on Arctic Ocean sea ice. Initially by means of highly-directive sonars from nuclear submarines, latterly from moving vehicles such as torpedoes. (Refs. D2, D4, D6, D9). The echo records are routinely of high quality, and taken over hundreds of miles of transects. In addition, fixed sea-bed units have also been used. (Ref. D5)
- Here again, the reason that the intrinsic resolution is much better than with radar is that the wavelength is one, sometimes two, orders of magnitude smaller.
- As a general comment, increasing directivity leads to better resolution.....both for acoustic and for radar impulse methods. However, this particular acoustic approach allows and can achieve two orders of magnitude improvement in transmission directivity [Approx. 1° versus about 50°].
- A possibly troublesome factor.....whose evaluation would be one of the objectives of a field trial.....is the extent to which particles in rivers other than frazil would produce confusing acoustic reflections.

Such particles would include suspended sediment, air bubbles, microscopic biota, etc. The degree to which echoes from these objects replicated echoes from frazil crystals, frazil clusters and ice sheets deserves examination. It is possible that the problem would not be too severe.

- The second major advantage (with bottomside sounding) is that this is the only method (short of helicopter use) which provides fully-operative, quality data in unsafe conditions of severe melting, actual breakup, and incipient ice jamming. Thus such an arrangement could monitor river ice dynamics in critical spots and at the critical break-up times.
- Field usage would be either by transects across a river, or time-series spot measurements. Operationally, this method would probably be restricted to standard WSC stations, because a tube or pipe on the bottom would be needed. (Fig. 7.1.)
- However, a feasibility demonstration to show the effectiveness of the technique would be much simpler and involve little more than submerging an existing directive acoustic sounder under the ice for very limited periods. (Figure 7.2)
- A competent and experienced Canadian company does exist for this specialist technology, and demonstration hardware can be relatively easily obtained.

8.0 "INDUCED-CURRENT" ELECTROMAGNETIC SUBSURFACE PROBING

(Although it is not yet fully clear whether a functionally-valid existing device can be obtained for demonstration without development, this method is listed here as being potentially promising.....though probably in the longer term.)

- The technique is predominantly magnetic in principle, based on inductive coupling and induced-current ("eddy current") effects in subsurface resistive layers. It operates at low AC frequencies. It would involve a transmitting/receiving pair of small coils, probably on a sled. (Figure 8.1). The signal in the receiving coil is, in part, dependent upon the dimensions of the different resistive layers below the coils.....in our case, the ice and water layers.

- This technique is 100% proven in the geophysics field.....routinely used for measurement of the dimensions of conductive ore bodies. (Also, non-conductive layers.) (Ref. C1)
- This technique was developed by and is proprietary to a Canadian company who certainly have the necessary technology and expertise.
- Our application would use a scaled-down version of this proven geophysical system. That is, rather than flying large coils hundreds of feet high to detect large resistive anomalies hundreds of feet deep, this version would "fly" two small coils on a sled close to the ice, to probe layers less than a metre thick.
- It is of course based on the resistivity differences between freshwater, freshwater ice, and frazil slush. The literature shows that these resistivity values may not be simple or constant in behaviour.....and this would have to be carefully examined. (Again, pre-calibration may be possible.)
- The signal processing is fairly complex.....though perhaps compatible with a portable instrument, given modern microprocessor technology.
- This proposed technique may well go ahead for the sea-ice application regardless of whether IWD is interested or not.
- Obtainable, field demonstrable, equipment suitable for conducting a valid field-experiment probably does not exist at the time of writing, and to create it for a forthcoming experiment would probably require more funds than exist this year. Also, it is preferable that exploratory computer modelling should preceed any hardware activity at all.

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The positive factors for this technique are a) it is fully proven, for larger geometries, b) a competent Canadian company exists to do it, c) an acceptable instrument would be 100% portable and snowmobile-compatible.....2 coils and a field instrument with display, moved over the ice without contact, d) a U.P. development seems feasible, and perhaps will develop, for sea ice, e) a phased step-by-step program limits commitment.

The negative factors are a) LF resistivity of freshwater-ice in its various phases may be too variable a natural property, and this needs examination, b) sensitivity analysis might show an inadequate spatial resolution, c) the data processing, even streamlined, may prove too complex for a portable instrument.

A more cautious, step-by-step program approach seems better advised in this case. A field demonstration this winter (unless existing equipment is almost optimum) might well be invalid, premature, and jeopardise a later orderly development. Though early computer modelling for a proper study could definitely be done in one or two months.

9.0 FINAL RECOMMENDATIONS

Sections 5, 6, 7, 8 above have reviewed recent work in the four most promising instrumental methods for measuring ice-thickness (and frazil concentration). The pro's and con's of each of the four techniques have been briefly described, together with their present status or state-of-the-art. Each of these separate techniques.....

- o Electromagnetic Subsurface Profiling by Impulse Radar
- o Acoustic Upwards Echo-Ranging (from the bottom)
- o Ultrasonic Thickness Gauging (using surface contact)
- (o Induced-Current Subsurface Probing.....possibly, if in time)

.....has been briefly described, together with their present status or state-of-the-art.

From this review certain important deductions must be presented as preamble before proceeding to any specific recommendation for action.

Firstly, although each technique has been shown in earlier work to have, at times, some promising and visible degree of success, as can be deduced from the overall discussion, in none of the four measuring-methods described was there an existing off-the-shelf operator-useable instrument which could be passed to a WSC field-technician for immediate use as a regular field instrument. Neither impulse radar-with-display, nor topside sonic-gage with-display, nor induction-transceiver-with-display, nor bottomside acoustic-sounder-with-display exist at present in a physical form which is readily portable and wholly compatible with snowmobile operation in extremely cold conditions.

Secondly, there is considered to be at this time no one single outstandingly-superior or quasi-ideal method for such ice-thickness measurement. Had there been such, in all likelihood it would have emerged and been widely accepted many years ago. (Which is not to say that the steady progress of technology may not result in a preferred method emerging in future.)

Thirdly, without going into details, there is, for the instrumentation examples discussed above, much conflicting evidence (and reportage) as to whether they work fairly well, impressively well, marginally or unimpressively. That is, there is a wide scatter in reported data quality. This, however, is not unusual, in any technological field at the frontier of the state-of-the-art, where this year's design can have improved features last year's design lacked.

[Some thought was given.....provided no hardware development was involved and providing existing equipment could as expected be obtained.....to performing a multiple intercomparison and multiple feasibility demonstration at the same ice site; at the same time; and in the same range of ice/frazil conditions. Such an intercomparison has never been done. However, as Appendix (2) shows, the overall costs and effort required for four simultaneous experiments, however worthwhile, exceeds present budget.]

Accordingly, taking into consideration all the factors discussed so far, it is recommended that hardware-demonstration/evaluation-effort be concentrated on what appears to be the most-generally-effective technique..... subsurface impulse-radar profiling, and specifically the broadband subset of this class of instrumentation.

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o "Impulse-Radar Subsurface Profiling: Specific Action Plan

The most suitable, high-resolution, commercially-available impulse radar could be procured (rental seems impossible) from a Canadian or U.S. manufacturer for this field-evaluation and demonstration. This radar is the broadband (untuned) UHF single impulse instrument specifically designed to penetrate short-range subsurface layers with different reflecting horizons. The instrument with its recorder/display would be towed on a sled by snowmobile, as sketched in Figure 9.1.

The verbally-quoted per-unit cost of this radar is $27k (U.S.) corresponding approximately to $35K Canadian, and additional special tests may increase this by a further $5K (Can.) which should be taken as the present best budgetary estimate. It must be stressed that, as this is written, a detailed supplier-negotiation covering all contracted tasks, and all instrument modules, has not yet been performed. Such awaits approval-in-principle. [The best-recognized supplier, it may be noted, grosses several $M each year selling these radars to geophysical prospecting organizations.]

The planned program of work pertaining to this instrument will be as follows. First will be monitored inplant electromagnetic tests, both transmission and reception. Second will be idealized electromagnetic resolution tests. Third will be controlled ice-simulations inhouse. Fourth will be signal-analysis and propagation predictions. Finally, following sled-installation at CCIW, will be the winter river-ice demonstration and trial.

The end-result or data-display will be in the form of a conventional "echogram".....that is, ice-thickness on Y-axis; horizontal distance on X-axis; and trace-intensity corresponding to intensity of reflections. [Format similar to a ships echo-sounder.] This type of data-display is the most informative and should provide a quality demonstration of what this impulse-radar profiling technique can achieve.

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Use of this radar will complement the other "ground-truth" events..... ice-core sampling and underice-TV observation and image-recording.

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30. Communications re ice-radar technology with staff of....CRC, AES, IWD, CRL, DOT, Barringer, CRREL, Instrumar, GSSI, etc.

(B) <u>Ultrasonic Thickness Gauging</u>

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2. "Ultrasonic Pulse Measurements of Anisotropic Lake Ice". Roethlisberger. CRREL Report 126 (1966).
3. "A Sonic Device for Measuring Thickness Changes at the Bottom of Floating Ice". Untersteiner. Antartic Journal of the United States. (Sept. 1966).
4. "Ultrasonic Investigations of Ice". NRC Lab. Report LTR-LT-82A. (1978).
5. "Seismic Techniques for Measuring Ice-Thickness". Caulfield Engineering. (Private Communication) (1982).
6. Communications re ultrasonic-thickness-gaging technology with staff of.....CTF Systems, Balteau, NRC, KB-Aerotech, Caulfield Engineering, CSNDT, Techoscientific Ltd., etc.

(C) Induced-Current/Resistivity Subsurface Probing

1. "COTRAN Electromagnetic Survey System". Barringer Research Note P80-1039. (1980).
2. "An Instrument for the Measurement of Ice-Thickness in the Field". DRNL(DRB) Techn. Note 57/8.
3. "Two (Resistivity) Instruments for Measuring Ice-Thickness". DRNL (DRB) Techn. Note 61/5.
4. "The Electrical Propoerties of Snow and Ice". Journal of Glaciology. V 15, No. 73 (1975).

(D) Bottomside Acoustic Profiling

1. "Reflection of Sound at the Water/Sea-Ice Interface". Langleben. Journal of Geophysical Research. V 75. No. 27 (1970).
2. "Sea-Ice Bottomside Features in Denmark Strait". Journal of Geophysical Research. V 79. No. 30 (1974).
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4. "Analysis of Ice-Profiles Obtained by Submarine Sonar in the Beaufort Sea". Journal of Glaciology. V 25. No. 93 (1980).

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6. "Joint Topside/Bottomside Remote-Sensing Experiment on Arctic Sea-Ice". Proceedings 4th Canadian Symposium on Remote-Sensing. 1977.
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9. "Unmanned Arctic Research Submersible". APL Report UW-7219. University of Washington (1972).
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11. "Sea-Ice Pressure Ridges in the Beaufort Sea. (Acoustic Profiling of...)" IAHR Symposium on Ice Problems. (1978.)
12. "Theory of Non-Specular Reflection Effects of an Ultrasonic Beam Incident on a Solid-Plate in a Liquid". IEEE Transactions on Sonics. (March 1977).
13. "High-Resolution Observations of Underice Morphology". APL Report UW-7712. University of Washington (1977).
14. "Sonic Reflection from an Ice-Plate in Sea-Water". Physics Dept., Georgetown University. AD-A039868 (1977).
15. Communications re bottomside-acoustic-profiling technology with staff of.....APL, Mesotech, OSS, etc.

APPENDIX 1

"Extract from Minutes of November Meeting
of the River-Ice Subcommittee"

2. ICE THICKNESS MEASUREMENT DEVICE

This device would be designed for the convenient measurement of the thickness of an ice cover.

The portability of the device was discussed. It was felt that it should be less than 50 lbs in weight if it is to be carried or hauled on a toboggan. It should be useable on six or more inches of ice.

The relative advantages of an instrument which could provide continuous recording of ice thickness versus one which takes point measurements were discussed. The former type of instrument was deemed more desirable.

The adaptability of the proposed instrument was discussed. It was mentioned that the instrument should be adaptable to a variety of field conditions and river depths.

It was agreed that the instrument should be developed for the convenient measurement of the thickness of ice in a consolidated ice cover, but that there would be many advantages to eventually having an instrument which could measure the thickness of a partial ice cover or an ice jam.

The possible complexity of an ice cover was discussed. There could be several different layers of snow, ice, water and slush. Dr. Davar suggested that the determination of the overall physical dimensions of the ice (solid and frazl) was more important than the identification of the various layers.

Mr. Ford inquired as to the electronics ability of people who would use the instrument. He was told that they would probably have technical training but not necessarily in electronics.

Mr. Ford asked what the desired accuracy of the instrument should be. It was suggested that it should be accurate to 30 mm (0.1 ft) on all measurements of ice thickness.

Attachment one to the minutes of the November 23 meeting of the Subcommittee on River Ice (Local Working Group):

INSTRUMENTS FOR THE OBSERVATION OR MEASUREMENT OF RIVER ICE

In order to undertake operational and research work on river ice in a more efficient manner, the development of the following instruments is suggested:

1. ICE THICKNESS MEASUREMENT DEVICE

The instrument should be designed for the convenient measurement of the thickness of a river ice cover. Ideally, the instrument should automatically chart and record the ice thickness as it is moved longitudinally or transversely across the ice cover, and would not require the drilling of holes in the ice cover. The sensitivity of the measuring device should be adjustable to the type, density and depth of ice being encountered.

GENERAL REQUIREMENTS:

All instruments should be:

1. PORTABLE

The instruments should be designed so that they can be easily carried or towed over the ice cover by one person. The ease of transporting the instrument up and down steep river banks should be also considered.

2. ADAPTABLE

The instrument should be adaptable to a variety of field conditions found throughout Canada. Particularly important will be the range of temperatures and humidity in which the instruments can be reliably operated. The instruments should also be usable on both shallow and deep rivers.

3. AFFORDABLE

It is hoped that instruments could be developed which can be suitable for operational use, as well as, research applications. Instruments that may eventually be produced at costs affordable to small government agencies and consulting firms would be desirable.

In addition, the instruments should be designed so as to be easy to operate, test, calibrate, and repair.

APPENDIX 2

Estimates for Demonstrating Alternative Techniques
(for record only)

This appendix summarizes what would be needed if any of the alternative (non-radar) techniques were to be evaluated, as may in future become possible and justifiable. The following comments apply.

First, because no existing, proven, "cold-weather-portable", instrument has yet been packaged, these estimates are based on applying the next best.....a functionally-representative instrumentation-ensemble not yet miniaturized for portability, or ruggedized for winter field use, ...but which would produce valid data.

Secondly, it should be noted that each "field-demo" has been coupled with an attempt at instrument calibration, controlled local simulations, and signal-analysis. [That is, each test attempt not just qualitative, but some quantitative findings.]

Third, this preliminary verbal estimate (without commitment) was obtained from one supplier of each option. Generally from these contacts, the impression was obtained (not surprisingly) that, contracting with about $10K one obtained very little; whereas with about $25K one could probably do a worthwhile experiment and evaluation.

Fourth, whether to go sole-source (excluding marginal suppliers), or multiple-bid has not yet been seriously addressed.

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o Ultrasonic Thickness Gauging: A conventional, but high quality and high resolution, ultrasonic thickness gauge such as used for Industrial Non-Destructive Testing (NDT), would be obtained.....rented or borrowed. (Almost certainly it will be an imported instrument.) The ultrasonic probe would be put in best contact with the ice, with best coupling, probably using oil. (Both fixed-transducer and wheel-transducer would be tested.) The signal reflections from the ice and perhaps the frazil will be displayed at the time (probably by scope) and magtape-recorded for later analysis in the laboratory.

In parallel, and probably from a Canadian specialist company in non-destructive testing, a theoretical calculation of expected signal-amplitudes would be prepared.....so that the experimental and predicted values could be intercompared.

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- Review/select/obtain sonic-thickness gauge plus recorder	=	Approx. $15K to $20K
- Local cold-room tests and simulations	=	
- Acoustic pathloss calculations and signal prediction	=	
- Winter river ice tests and contractor report	=	

Several specialist suppliers or consultants have been contacted. All are keenly interested. Multiple bidding would be unavoidable for any contract action.

o <u>Acoustic Upwards Echo-Ranging:</u> A high resolution acoustic sounder in a submersible package would be obtained (rented or borrowed) from the Canadian specialist supplier for a feasibility demonstration. Frazil and ice signals would be displayed on a separate high resolution echo-sounder-type recorder.

As shown in Figure 7.2, each test will involve moving the acoustic sounder horizontally for 10 or so metres along a single bottom-mounted guide rail, under manual, diver, control. Thus as the sounder transmits upwards, a short section of "inverted" echogram will be profiled, displaying both ice thickness and frazil-slush accumulations. An intercomparison of these experimental signal amplitudes versus the theoretically calculated signal amplitudes would be prepared. (As before inplant calibrations would preceed field-work.)

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- Plant-based resolution tests, simulations, etc.	= $9K	Approx. $25K to $30K
- Propagation analysis, signal-analysis, etc.	= $8K	
- Field experiment, rental, and report. (Travel excl.)	= $9K	

(This is a sole-source Canadian supplier situation.)

o <u>Induced-Current Subsurface Probing:</u> In this case the sequence would be as follows. The natural variability of LF bulk-resistivity of freshwater ice would be carefully confirmed. This would input to existing computer models, perhaps with some reprogramming for this geometry. A theoretical analysis using idealised multilayers would then be run to give predicted signal responses. An optimization process (frequencies, spacing, power, etc.) would follow. If the best system arrangement showed adequate predicted resolvability (i.e., signal/noise ratios), then hardware action would commence. Demonstration tests on simulated resistive layers would be done in plant, and a field demonstration on winter ice.....first locally, and then at site.

- Confirm resistivity patterns for low-molarity ices	= N/C (IWD)?	
- Perform computer-analysis to model and predict the induced-current patterns for dual resistance layers	= $10K	
- If existing equipment suitable, perform inplant controlled simulation on mulitple layers	= ?	Approx. $20K
- If simulations OK, perform field-ice demonstration and analyse data. Contractor report	= ?	

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The above will give some indication of what would be involved in a feasibility-demonstration of the alternative methods. It was noted in all cases that the various specialist suppliers contacted were very interested, and appeared to provide realistic verbal estimates.

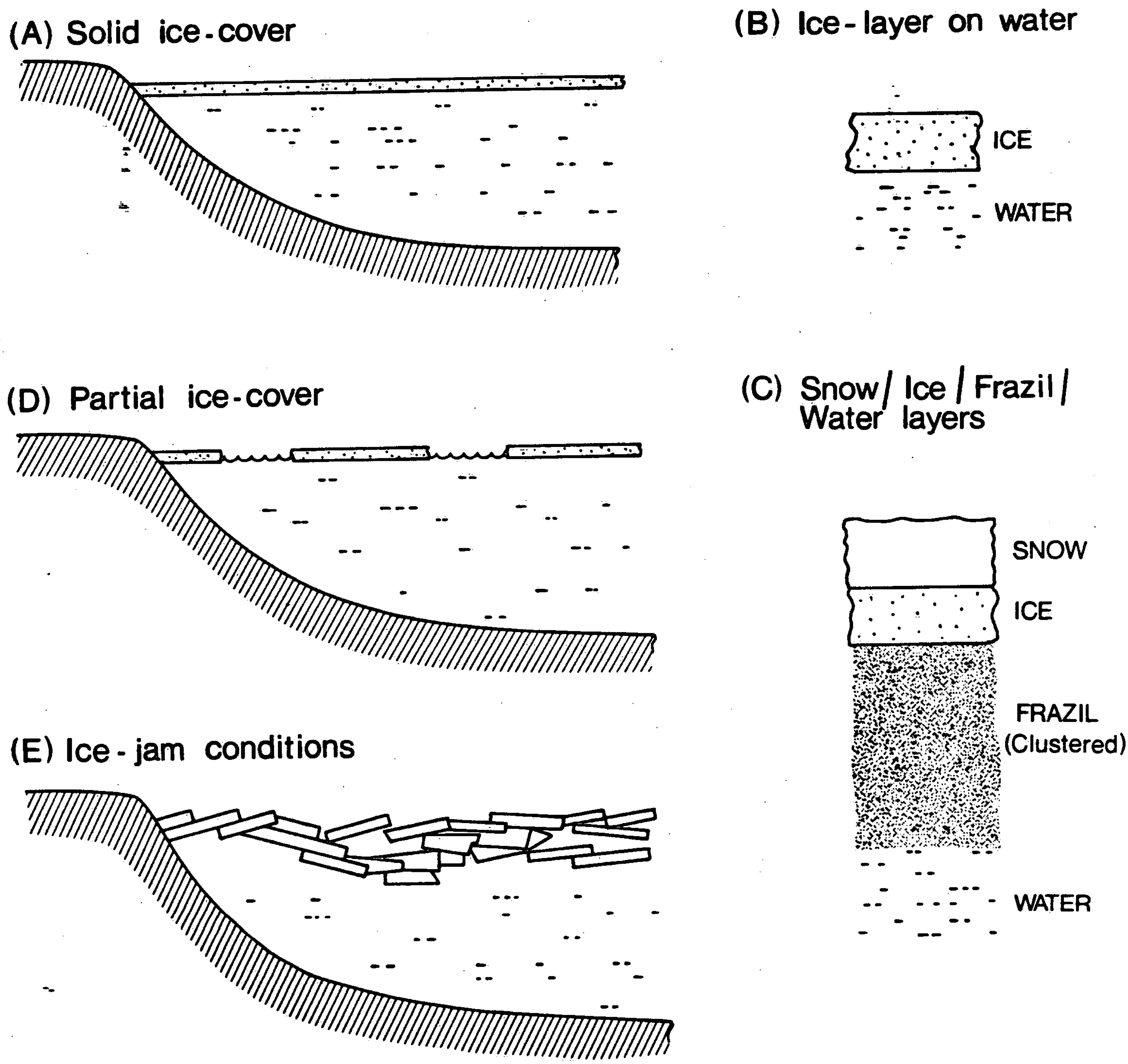


Figure 4.1 VARIOUS FIELD CONDITIONS, FOR RIVER-ICE MEASUREMENT.

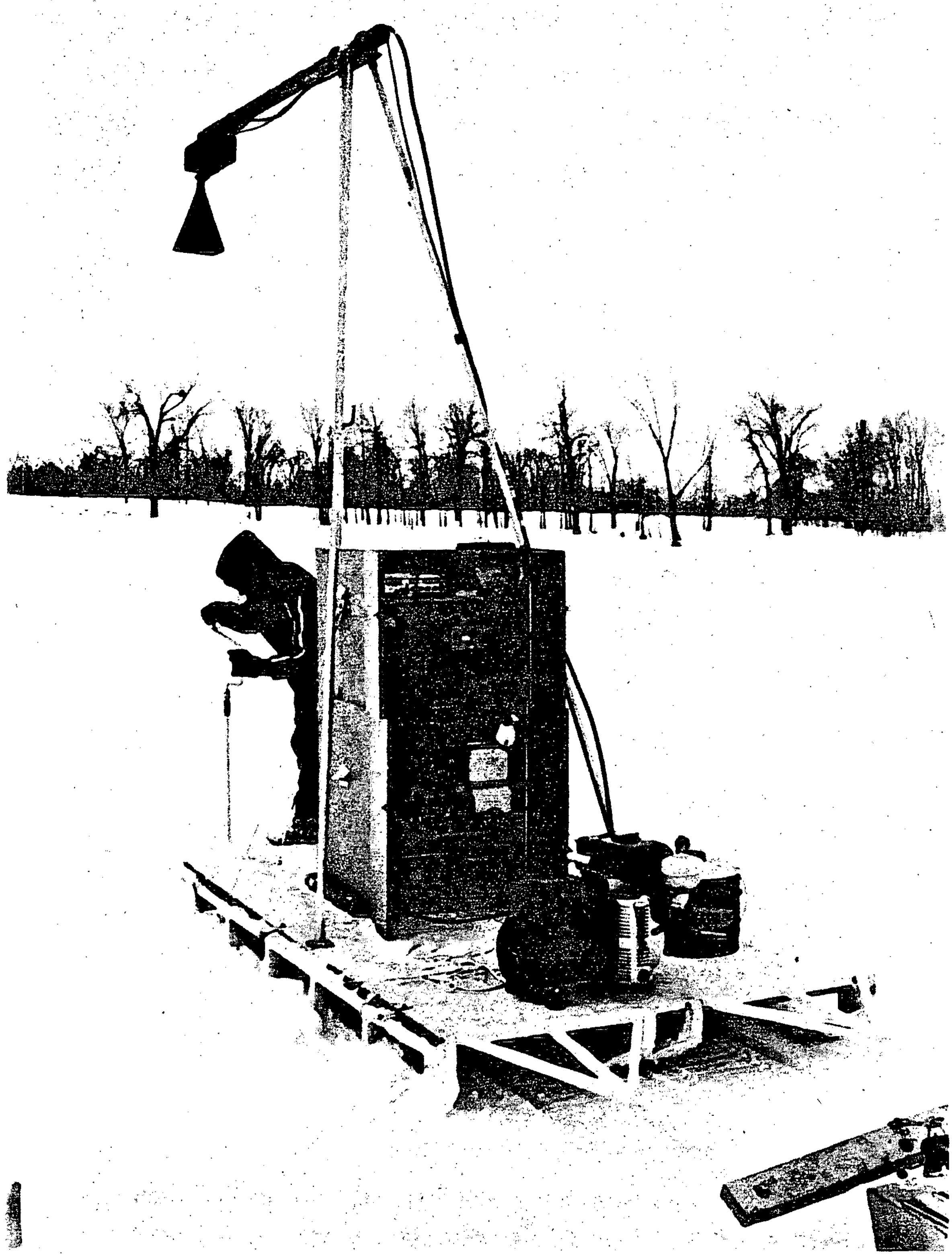


Figure 5.1 TYPICAL EXPERIMENTAL IMPULSE - RADAR USED FOR DEMONSTRATING THE FEASIBILITY OF ICE-THICKNESS MEASUREMENT.

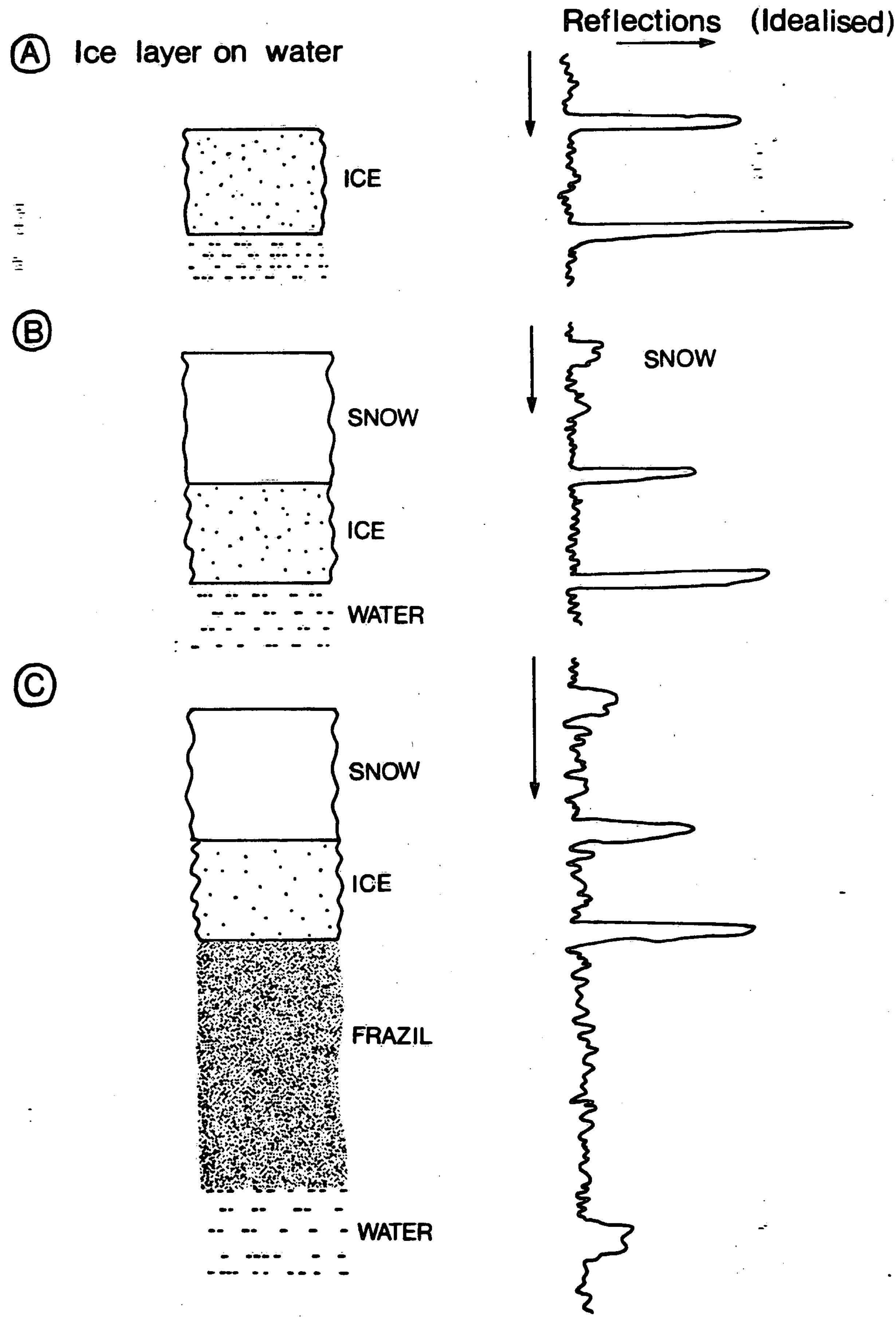


Figure 5.2 ELECTROMAGNETIC REFLECTION GEOMETRIES

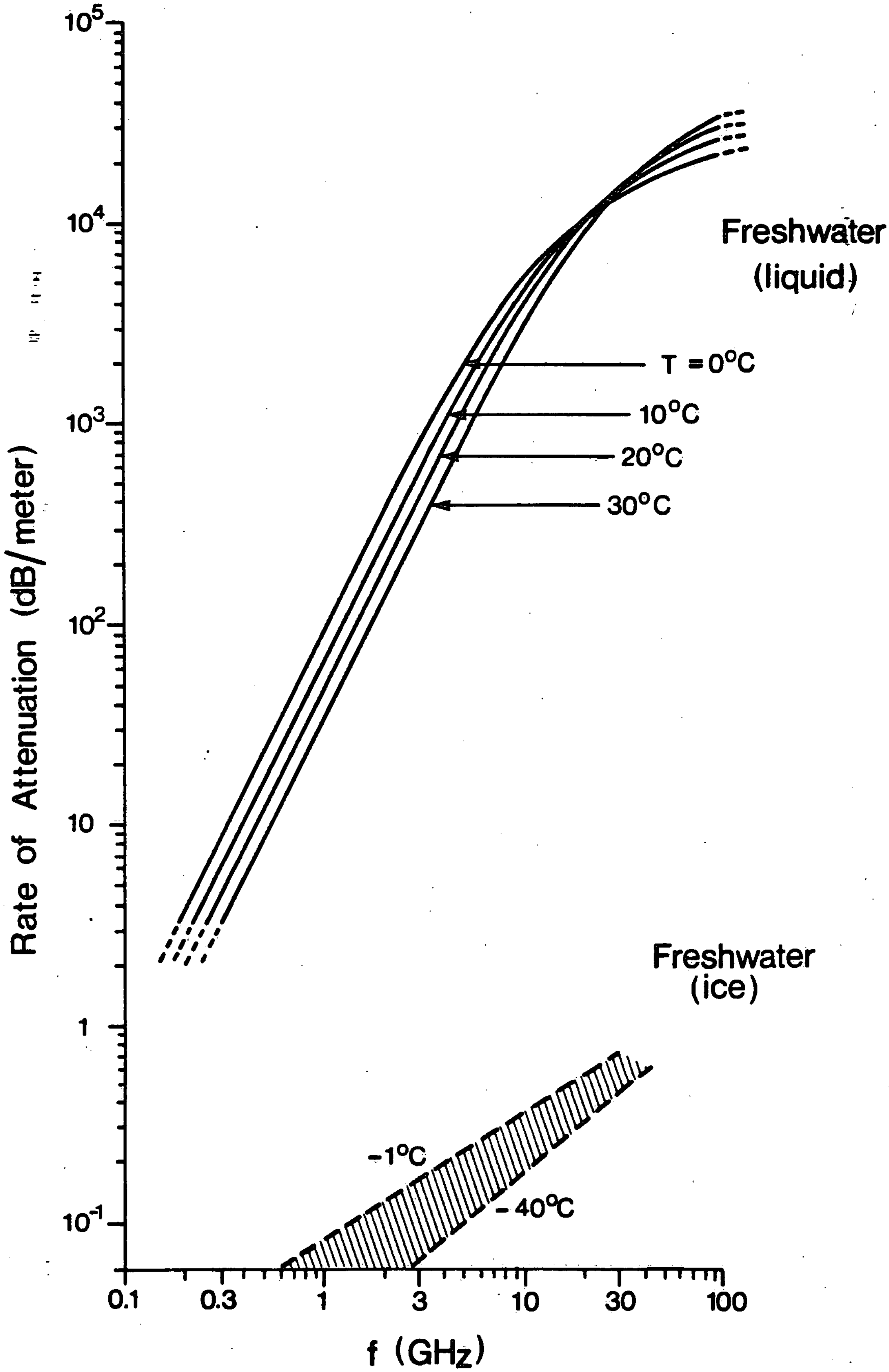


Figure 5.3 ELECTROMAGNETIC - WAVE ATTENUATION

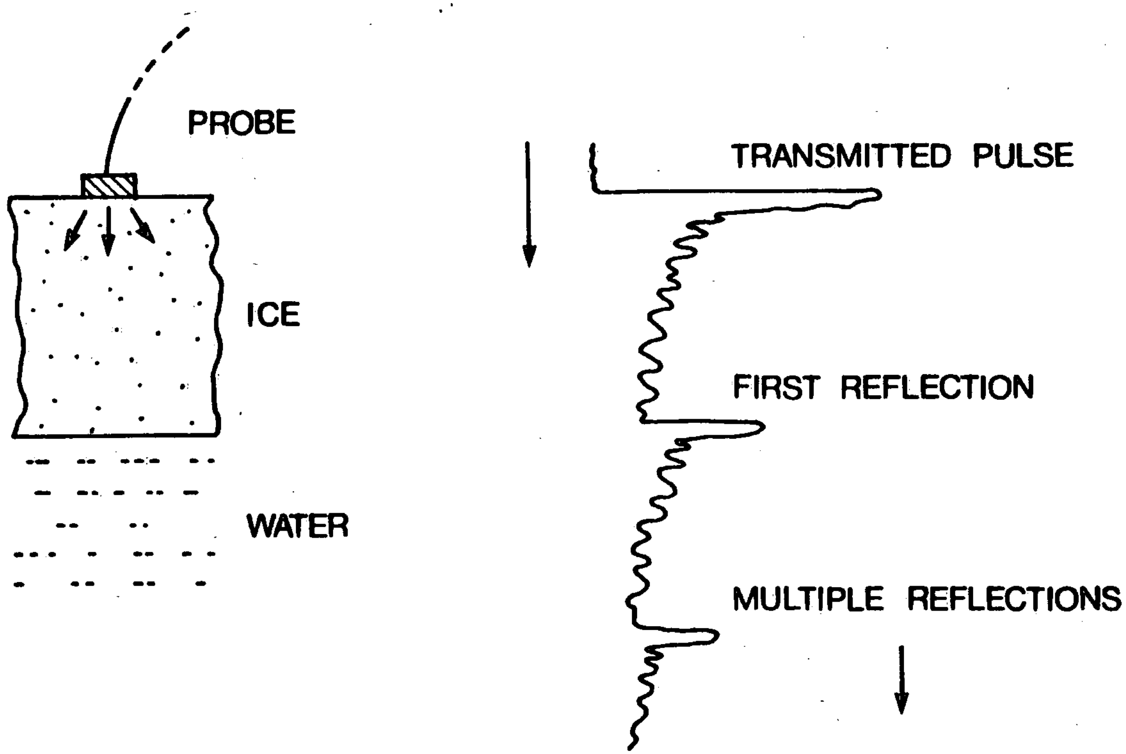


Figure 6.1 ULTRASONIC THICKNESS MEASUREMENT OF AN ICE-SHEET

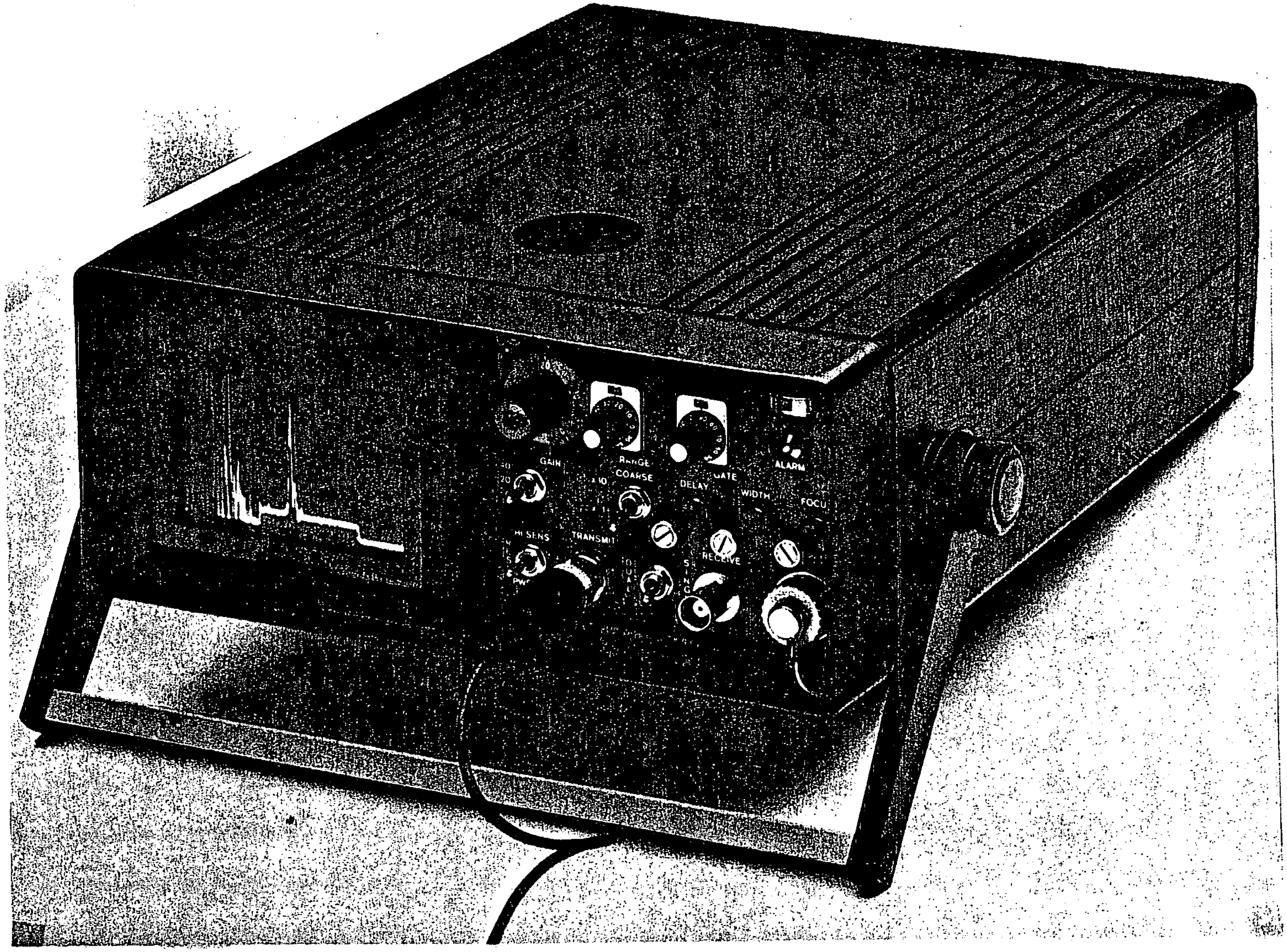


Figure 6.2 TYPICAL COMMERCIAL ULTRASONIC THICKNESS GAUGE.

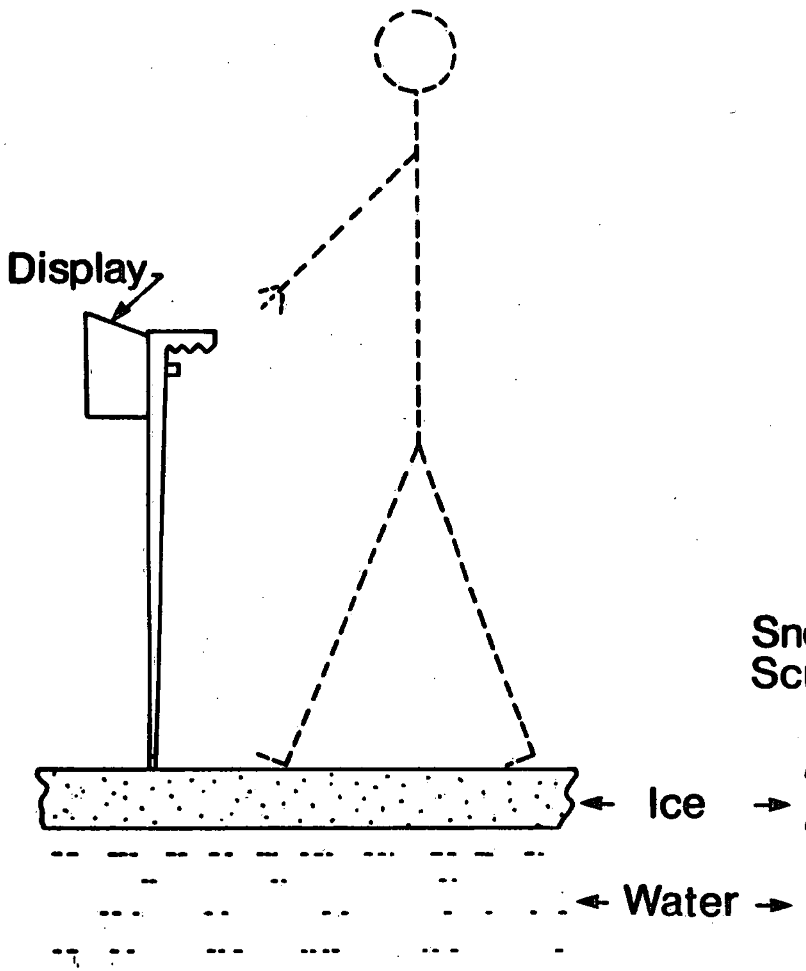


Figure 6.3

PORTABLE THICKNESS GAUGE
FOR SPOT MEASUREMENTS

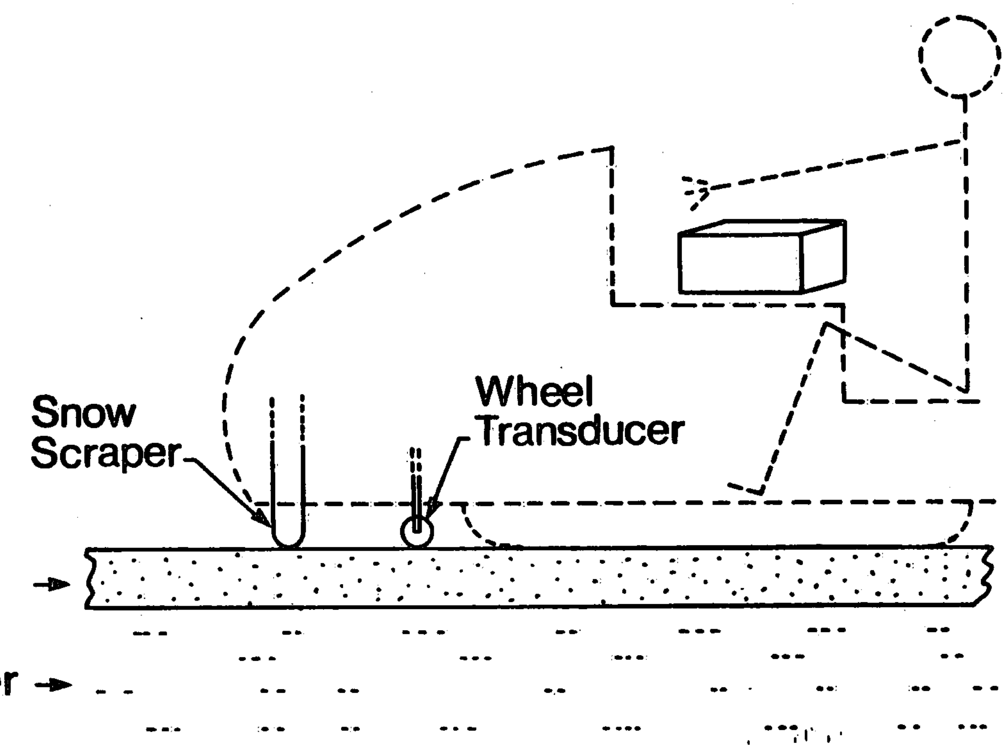
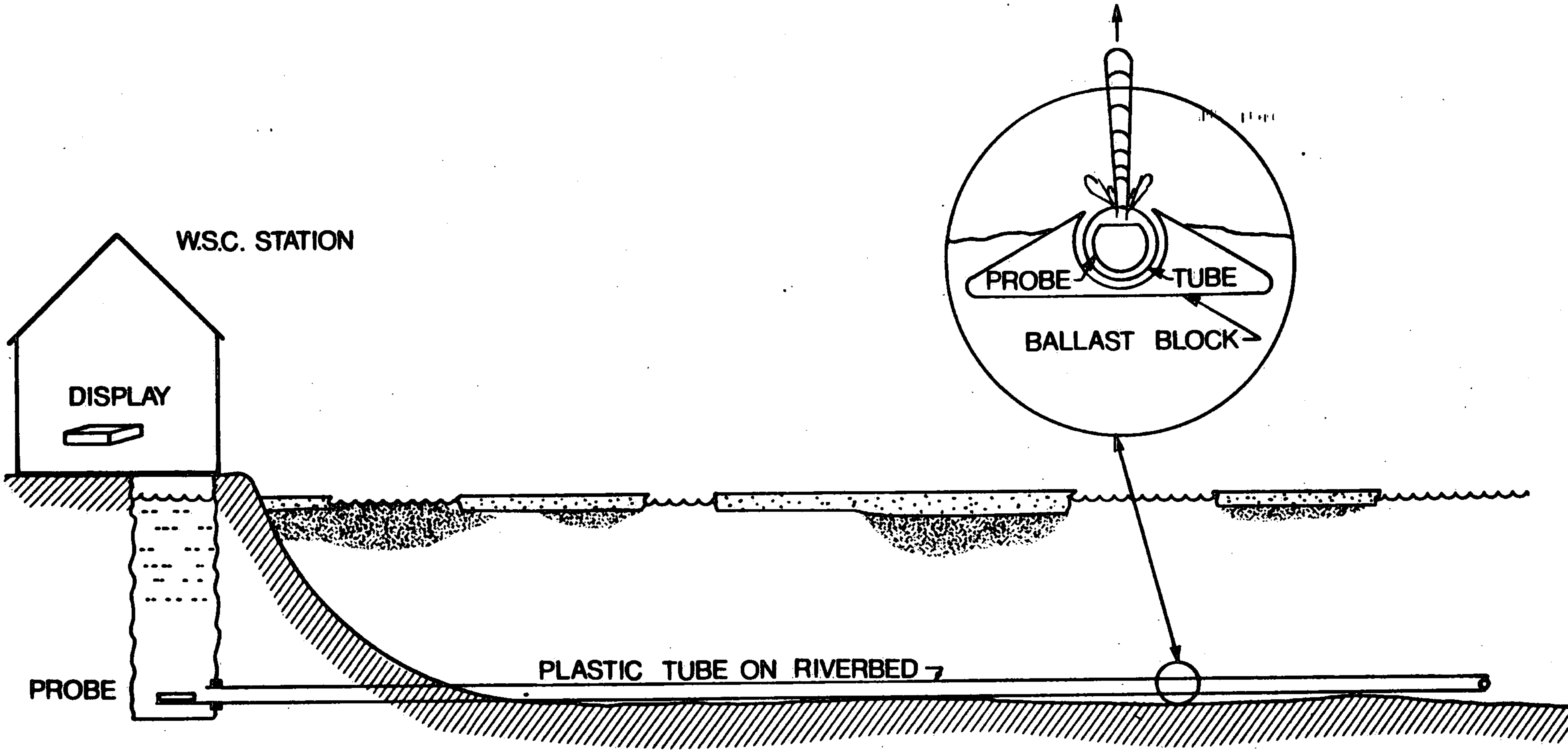


Figure 6.4

SNOWMOBILE VERSION : CONTINUOUS
GAUGING TO PRODUCE THICKNESS PROFILE



MODUS - OPERANDI

- ARRIVE CARRYING INSTRUMENT. PUT PROBE IN MOVABLE "TRAY" IN STILLING-WELL.
- BY HAND, WINCH PROBE ALONG PLASTIC TUBE, PRODUCING CONTINUOUS PROFILE ON DISPLAY.
- WINCH PROBE BACK TO STILLING WELL. REMOVE INSTRUMENT. DRIVE TO NEXT STATION.

Figure 7.1 CONCEPT ARRANGEMENT FOR BOTTOMSIDE PROFILING ACOUSTICALLY

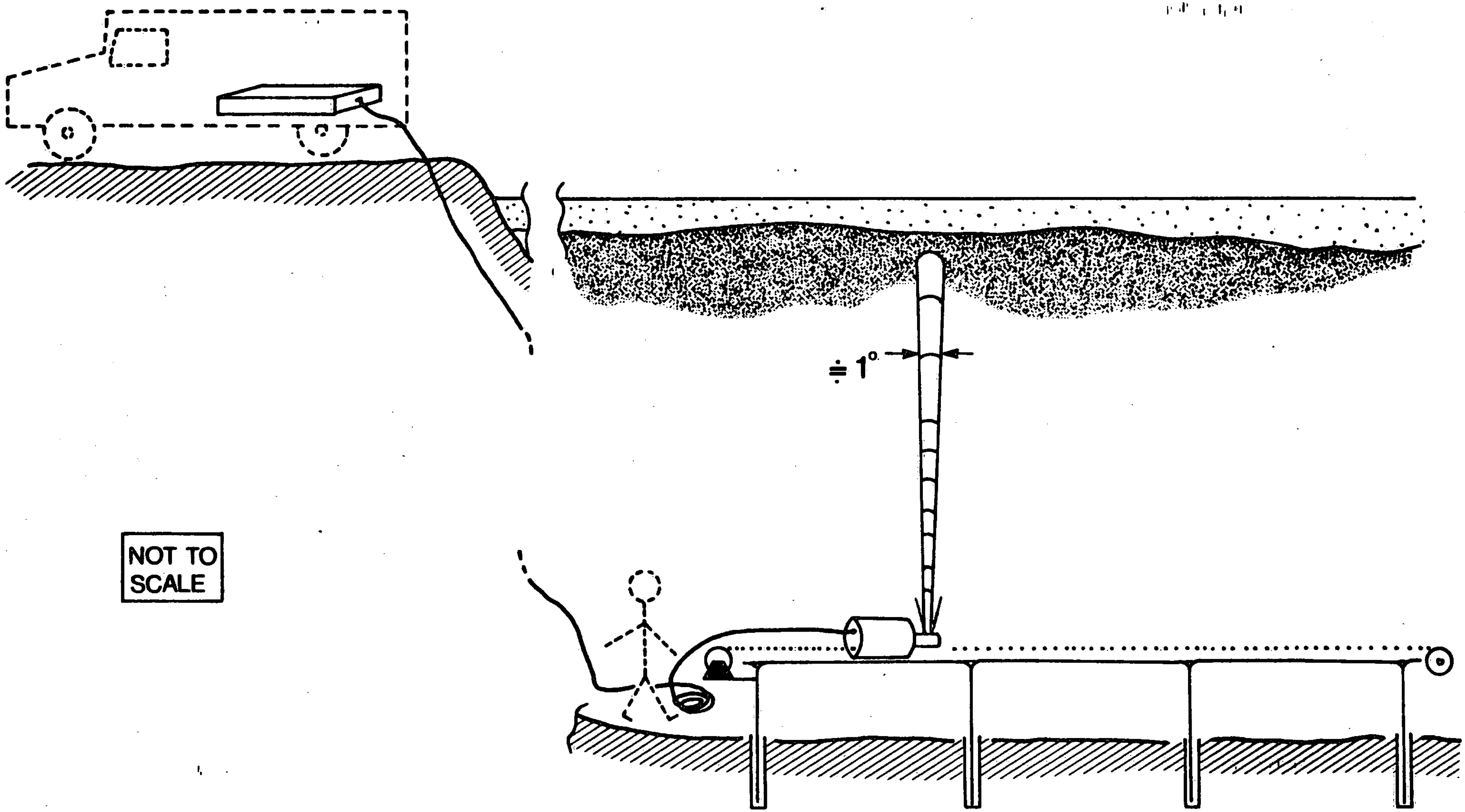


Figure 7.2 PROFILING BOTH ICE AND FRAZIL USING BOTTOMSIDE SOUNDING (FEASIBILITY DEMONSTRATION ONLY)

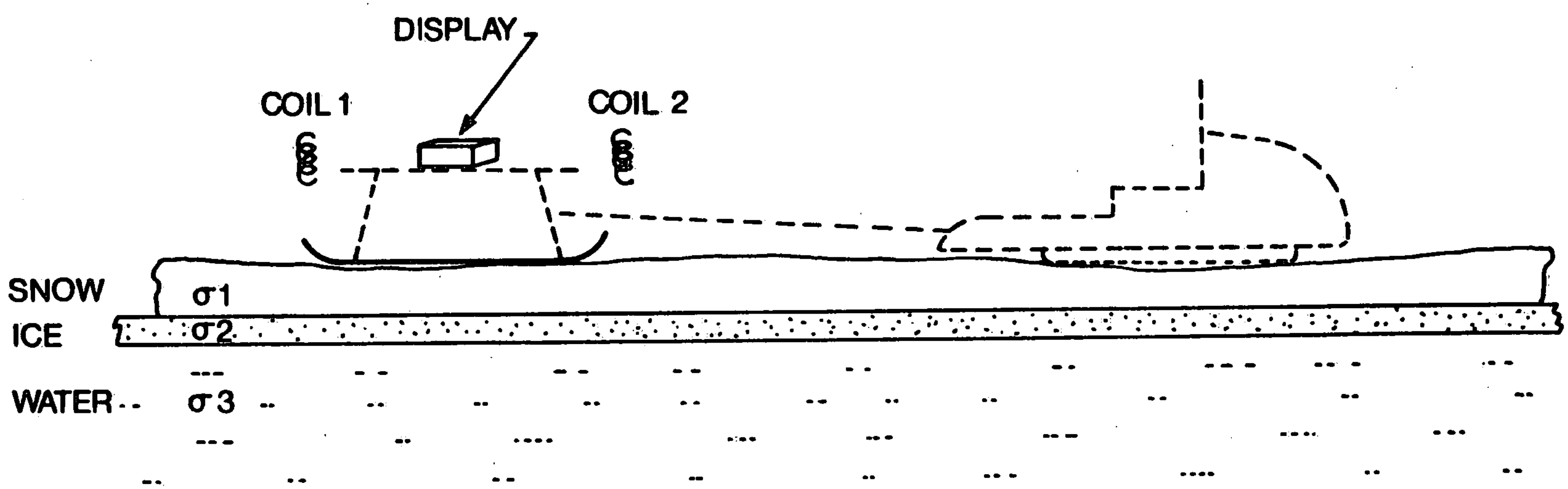


Figure 8.1 CONCEPT ARRANGEMENT : ELECTROMAGNETIC – INDUCTION TECHNIQUE.

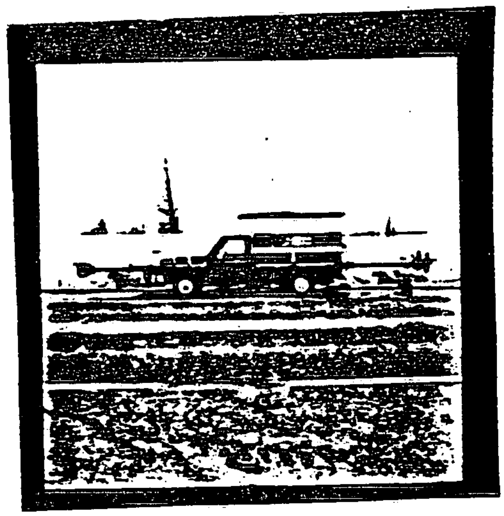


Figure 8.2 VAN- MOUNTED EMBODIMENT OF E.M. INDUCTION »THICKNESS-METER« SHOWING BOTH COILS.

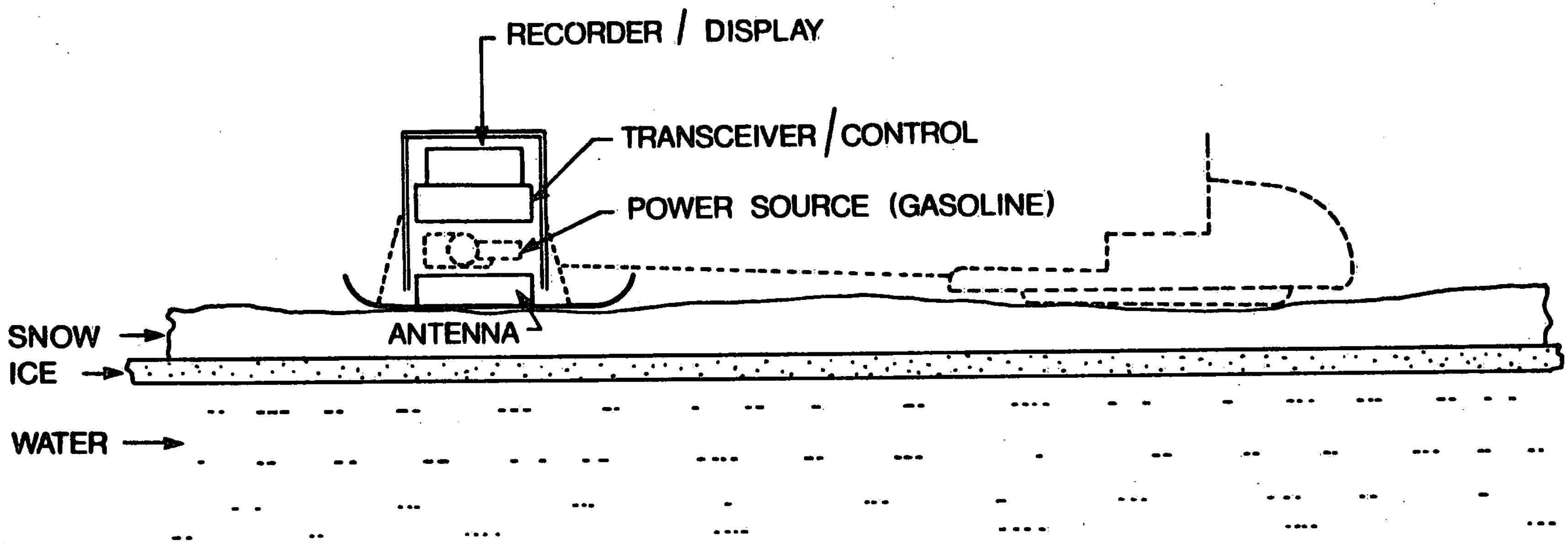


Figure 9.1 ARRANGEMENT FOR FIELD-DEMO OF COMMERCIAL IMPULSE-RADAR SYSTEM.

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