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Sincerely,

John C. Joseph
Vice President, Engineering

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A portable instrument that can be manually placed in contact with the surface of an ice-covered body of water to non-obtrusively measure the ice thickness was developed. The instrument design is based on determining ice thickness from microwave frequency signals which are transmitted through the ice and reflect from the ice/water interface. Prior methods include drilling through the ice to manually measure its thickness and using radar equipment which is costly, time consuming, and which produces data often difficult to interpret.

The ice measuring instrument produced under this contract meets its goals for performance and physical characteristics. Measurement range exceeds the required 2 to 24 inches with ½ inch accuracy. Ice measurements take 12 seconds on average, thickness processing takes 10 seconds, and calibration is performed in under 30 seconds. The instrument is fully portable; it is powered by an internal, rechargeable battery. The instrument is built into a transit case, which also houses all accessories. Overall dimensions are 20x14½x15 inches (LxWxH). Weight is 30½ lbs. Performance has been verified by measurement of ice 2 to 24 inches thick and by measurement of sheets of polyethylene 2 to 32 inches thick.

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SECTION 1

INTRODUCTION

This report summarizes the activities performed and accomplishments reached under contract DACA33-91-C-0030, "Development of a Portable Ice-Thickness Measuring Instrument". This project resulted from the Small Business Innovation Research (SBIR) program solicitation number 91.1, topic A91-020. The contract was sponsored by the Department of the Army, Cold Regions Research and Engineering Laboratory, Corps of Engineers, Hanover, New Hampshire.

The objective of this project was to develop a one-person portable instrument that can be manually placed in contact with the surface of an ice-covered body of water to non-obtrusively measure the ice thickness. The instrument design is based on determining ice thickness from microwave frequency signals which are transmitted through the ice and reflect from the ice/water interface. System goals include measurement of fresh-water ice from 2 to 24 inches thick with ½ inch accuracy and ability to measure ice in several locations in a short time. Prior methods include drilling through the ice to manually measure its thickness and using radar equipment which is costly, time consuming, and which produces data often difficult to interpret.

This effort was accomplished in two phases. The technical merit of the basic measurement approach was verified in phase I, from August 1991 to February 1992. A *breadboard model* was developed and used to experiment with measurement techniques and to evaluate different hardware schemes. The ability to transmit and receive microwave signals through the ice and the ability to accurately measure phase of the reflection were successfully demonstrated in phase I.

Development of the instrument was completed in phase II, from August 1992 to February 1994. The major tasks of phase II were to extend and refine the measurement approach; to design a reliable method of computing thickness from measured phase; to develop the final instrument assemblies; to embed the processing and instrument control functions; and to integrate, test, and evaluate the deliverable instrument. A photograph of the instrument in use appears in figure 1. The instrument is named the DE3146 Vector Reflection Analyzer.

The instrument consists of an electronics assembly built into a heavy duty transit case and a pyramidal horn antenna which attaches to the electronics assembly via a flexible microwave cable. The antenna is stored in the case and all accessories are stored in the cover of the case. A photograph of the instrument closed in its case appears in figure 2. Overall dimensions are 20x14½x15 inches (LxWxH) and weight is 30½ pounds. The instrument is powered by an internal battery. The battery can be recharged without being removed from the instrument. There is also a jack to allow operation from external power supplies. Ice measurements take an average of 12 seconds, processing the data to compute ice thickness takes about 10 seconds, and calibration is performed in under 30 seconds. Operator instructions and computed ice thickness are displayed alphanumerically.

The DE3146 was tested by measuring sheets of polyethylene, a 2.5 inch thick block of ice, a 22.6 inch thick block of ice, and natural lake ice. Polyethylene was used for most of the development testing because stacking it provided a practical means of measuring thickness in small steps over a wide range. The sheets used were 2 feet square and approximately 2 inches thick each. Thickness of the stack ranged from 2 to 32 inches. The dielectric constant of polyethylene was substituted for that of ice to perform the thickness calculations. Results obtained from the polyethylene measurements are presented in table I and from ice are presented in table II. Note that the instrument is programmed to round the measured thickness to the nearest tenth of an inch.

Figure 1. DE3146 Vector Reflection Analyzer

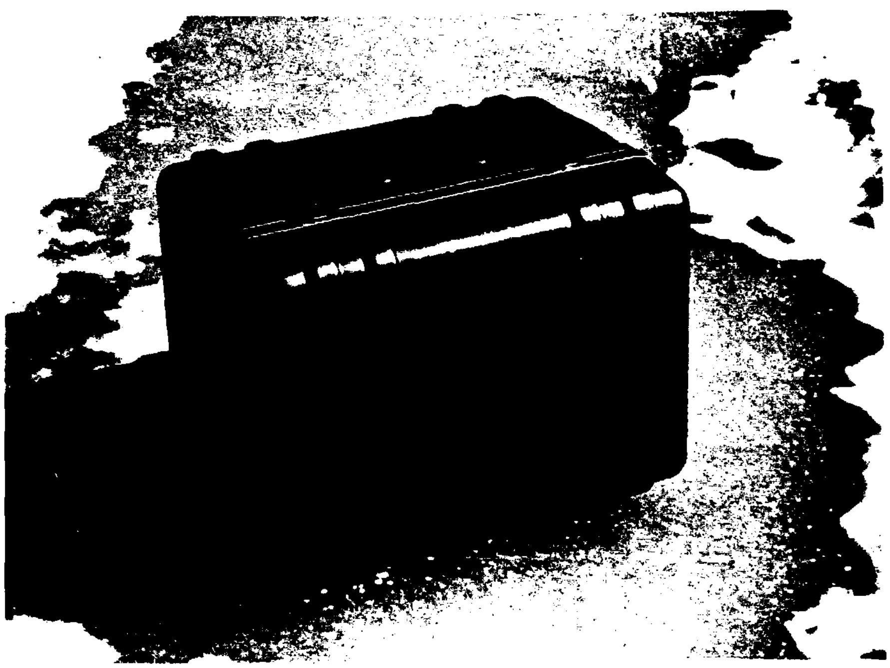


Figure 2. Instrument in Case

Table I. Polyethylene Data

Number of Sheets	Actual Thickness	Measured Thickness
1	2.23	2.2
2	4.46	4.6
3	6.59	6.7
4	8.72	8.7
5	10.94	10.8
6	13.04	13.4
7	15.13	15.0
8	17.23	17.2
9	19.39	19.6
10	21.52	21.4
11	23.70	23.6
12	25.87	25.7
13	28.05	27.9
14	30.17	30.1
15	32.36	32.3

Table II. Ice Data

Ice Sample	Actual Thickness	Measured Thickness
Block	2.46	2.4
Block	22.62	22.4
Lake	23.75	23.7

SECTION 2

SUMMARY OF PHASE I WORK

The objective of the Phase I effort was to verify the technical feasibility of the proposed approach to the ice thickness measuring instrument. The work performed during Phase I to accomplish this objective included:

- testing measured reflection versus predictions from the electrical model of the ice/water
- test of antenna and calibration approaches
- design of a method of converting the measured quantities to ice thickness
- development and test of a working "breadboard model" of the instrument

REFLECTION MEASUREMENT

The reflection off the ice/water is the sum of the *initial reflection* from the upper ice surface; the *single time around* signal which travels to the bottom of the ice, reflects off the water, and travels back to the antenna; and *multiple time around* signals, which reflect down and up through the ice more than once. The phase of the total reflection as a function of ice thickness is shown in figure 3. The model used to generate this phase trace did not include dissipation of the signals due to spreading, which becomes more significant as ice depth increases.

The model for predicting reflections from ice/water was tested by measuring reflections off delrin, an acetyl resin, backed by an aluminum plate. Measurements were performed by a network analyzer equipped with an antenna at its test port. The reflection off delrin/aluminum is very similar to that off ice/water for thicknesses up to about six inches. Measurements were made on 1 inch thick sheets of delrin stacked to yield total thicknesses from 1 to 5 inches in 1 inch increments. Measurement frequencies were 1100 and 1200 MHz. Average error was 12° for measurements averaging slightly over 360°.

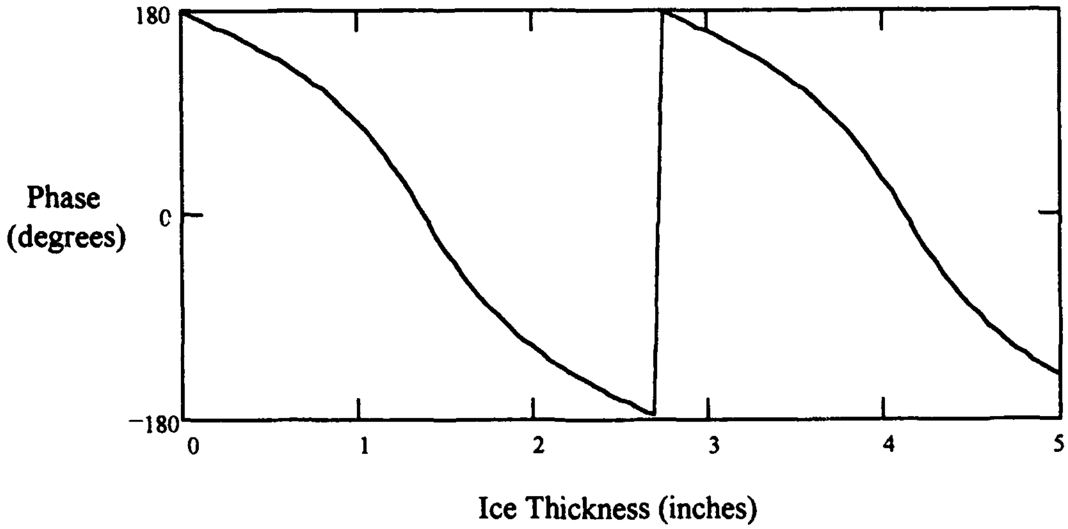


Figure 3. Phase versus Ice Thickness, 1200 MHz

ANTENNA AND CALIBRATION

Microstrip patch antennas were chosen for use because they could be tuned for very high return loss (40 dB) and because they offered size and cost advantages over other antenna types. High return loss reduces one source of measurement error. Test results indicated that antenna return loss must be at least 15 dB below the desired measurement signal to prevent significant error. The ability to accurately measure phase was tested by measuring phase versus height of an antenna positioned over a metal plate. Experiments were performed to investigate the effects of antenna height over ice to determine a suitable antenna height.

Calibration techniques were explored to correct for the two main sources of measurement error, frequency response error and directivity error. Frequency response error is caused by the variation versus frequency of the signal path beginning at the instrument's transmitter, through the antenna and the air above the ice, back through the antenna, and through the instrument's receiver. This error is removed by measuring the reflection off a known standard (a metal plate). Measuring the metal plate amounts to setting a calibration plane at the surface of the ice.

Directivity error is caused by undesired coupling of the instrument's transmitter to its receiver. Antenna return loss is typically the largest contributor to directivity error. The sum of all components comprising the directivity error can be measured by pointing the antenna into the sky and measuring the received signal. Since there is nothing to reflect transmitted signals back into the antenna, the measured reflection represents coupling internal to the instrument. One approach successfully used to correct for directivity error was to point the antennas into the sky while transmitting, and then tune the antennas to null the received signal. This makes the error small enough to neglect. A second approach successfully used was to measure the received signal with the antennas pointed into the sky, store the result, and mathematically subtract it from the ice and metal plate measurements.

THICKNESS COMPUTATION

The total phase change as a signal travels up and down through 24 inches of ice is about 3000 degrees at the frequencies used. Since phase is cyclic over 360 degrees, the observed phase is between 0° and 360°. This observed value represents the final or ending phase relative to the initial or starting phase. Ice thickness cannot be uniquely determined by measurement at a single frequency because the 360° observable range is traversed multiple times (see figure 3). The result is more than one ice thickness produces the same observable ending phase. We refer to this as phase ambiguity.

The phase ambiguity was resolved by performing the measurement at two different frequencies and searching for a thickness solution common to the two frequencies. The choice of frequencies dictates the maximum thickness that can be measured and the required accuracy in the individual phase measurements. Analytical expressions were derived relating measurement frequencies, maximum thickness, and required accuracy. The maximum measurable thickness increases as the frequencies are chosen closer together and the required accuracy becomes more stringent as the frequencies are chosen closer together. The required accuracy can be eased if more than two frequencies are used.

BREADBOARD MODEL

Key subassemblies of the ice measuring instrument were designed, built, and tested. These assemblies were then integrated into a breadboard model with the patch antennas, a battery, and panel meters to display measured voltages. These voltages were externally manipulated to calculate thickness. The breadboard model was used to measure sheets of delrin from ¼ inch to 6 inches thick. It was also used to measure two samples of ice, ¾ inches and 2¼ inches thick.

A synthesized transmitter assembly capable of producing frequencies from 800 to 1600 MHz was designed and developed. The module was optimized for frequencies of 1100 and 1200 MHz. Switching between the frequencies was accomplished by setting a front panel switch. These frequencies provided an unambiguous measurement range of 33 inches, but required a worst-case accuracy of 4 degrees in the individual phase measurements.

Tests were performed to examine the relative advantages of performing the phase detection directly at the measurement frequency versus down converting the received signals and performing the phase detection at a lower frequency. The latter approach was chosen and implemented in the breadboard receiver assembly because it was more accurate. It featured a coherent down conversion technique and a synchronous detection technique.

CONCLUSION

The phase I effort verified the feasibility of accurately measuring the reflection of microwave frequency signals from an ice-covered body of water with a portable, low-cost instrument.

SECTION 3

SUMMARY OF PHASE II WORK

The objective of the phase II effort was to produce a deliverable, ruggedized instrument capable of accurately measuring ice from 2 to 24 inches thick. Extending the capability demonstrated in phase I to measure 24 inches of ice proved to be a formidable task. Part way through phase II it was decided to change the manner in which ice thickness is determined from measured phase. The new method required more complex hardware, but the final product met the goals of accuracy, speed, and size. The major tasks of phase II were to develop the new measurement approach, including the thickness processing algorithm and calibration techniques; and to design and develop the instrument itself.

MEASUREMENT APPROACH

The new approach was to measure phase as a function of frequency. The phase change per frequency step can be held to much less than a full cycle (360°) by varying the frequency in small steps. The phase versus frequency data reveals the number of phase cycles encompassed over the frequency span. The total phase change over the span can then be calculated. Ice depth is unambiguously determined from the total phase change. Figure 4 shows the phase versus frequency for 2 inches and 24 inches of ice. The instrument steps from 3100 to 4600 MHz in 10 MHz increments. The points in the figure 4 phase traces represent the 151 measurement points.

Relative phase change from the first frequency to the last frequency is used to compute thickness rather than absolute phase at a single frequency. This makes the processing dependent on the frequency span but independent of the actual frequencies. The data can be gathered at higher microwave bands, where the bandwidth and antenna gain can be obtained with a single antenna of practical size. The ice thickness algorithm depends little on the phase accuracy at a single frequency. The algorithm does not bound the maximum thickness, whereas the

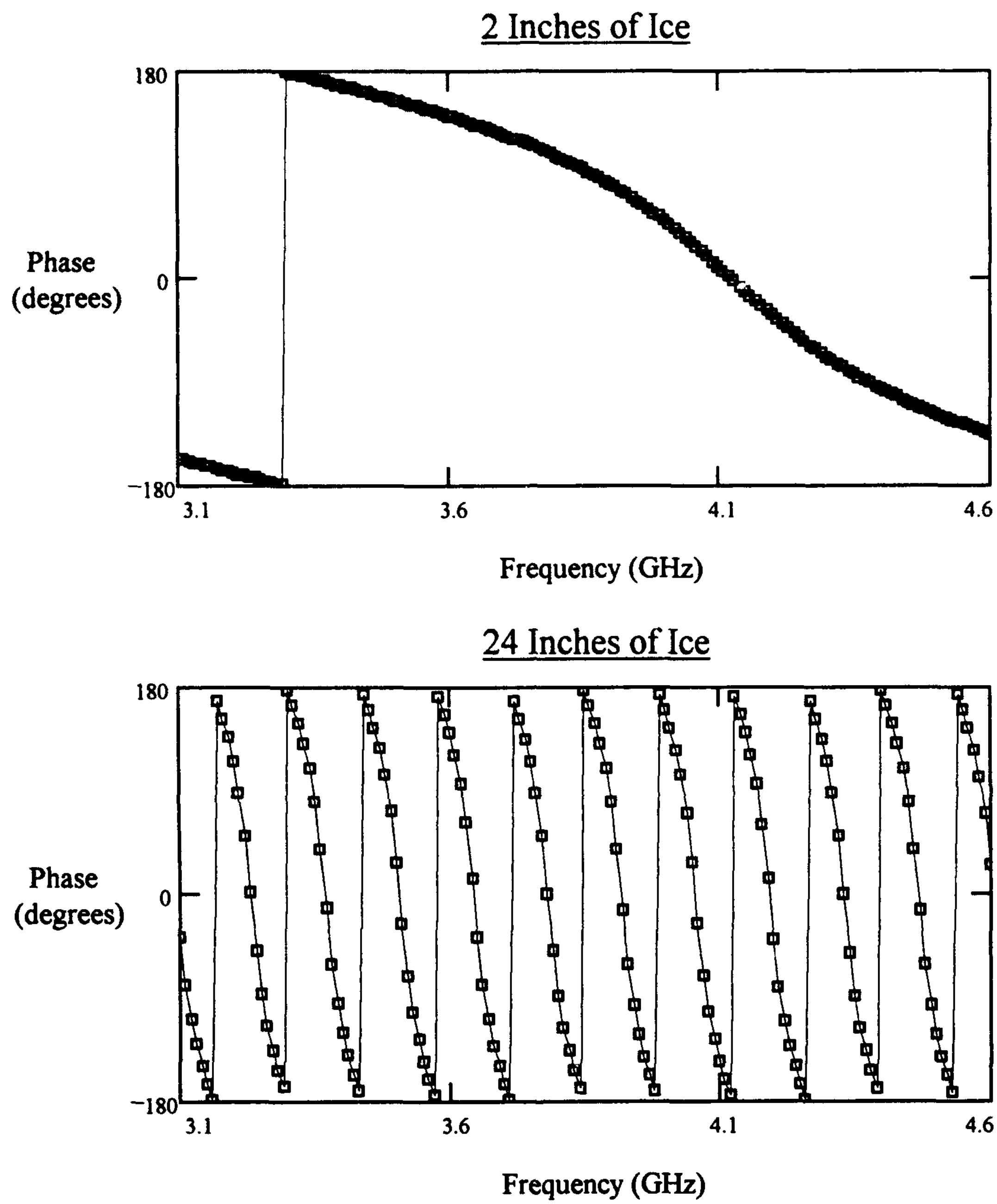


Figure 4. Phase versus Frequency

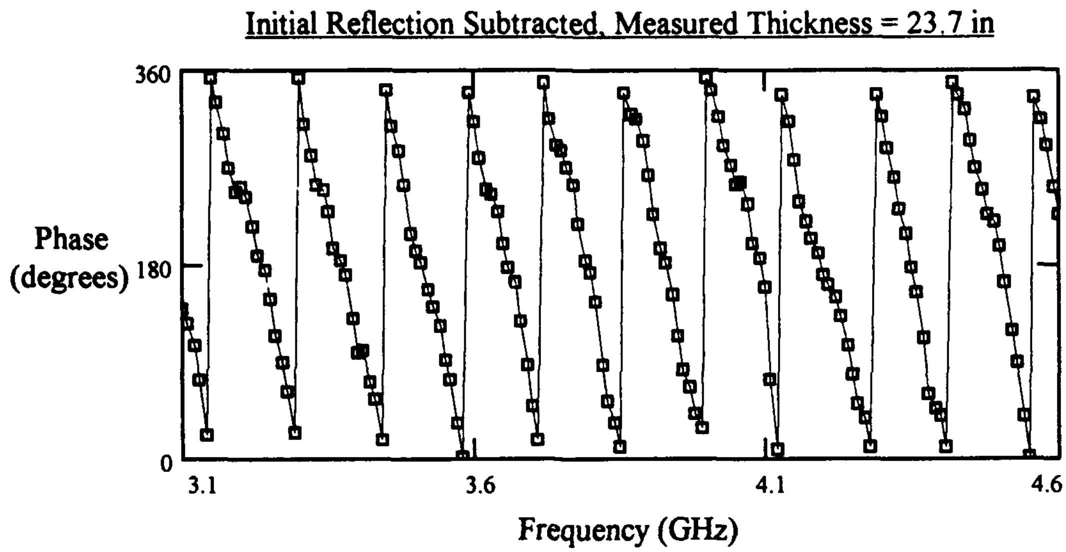
phase I approach was bounded by an unambiguous range. The algorithm is very tolerant of glitches in the measured phase, which would generally result in large errors with the original approach.

THICKNESS ALGORITHM

Ice thickness is calculated from a linear approximation of total phase change over frequency versus thickness. Although the phase of the single time around signal is linear versus thickness, the measured phase is not strictly linear because it consists of the sum of the single time around signal, the initial reflection from the upper surface, and multiple time around signals. The initial reflection can be calibrated out of the measured data since it occurs at the calibration plane and is itself accurately measured. Subtracting the initial reflection improves the linear approximation so that the maximum thickness error due to the approximation improves from 0.4 to 0.2 inches.

The initial reflection subtraction improves results in another more subtle, yet more significant way. The 0.4 inch error mentioned above applies only to small ice thicknesses (several inches). As the ice becomes thicker, the single time around and multiple time around signals are attenuated by spreading of the antenna beam. Eventually the measured reflection would be dominated by the initial reflection, which contains no thickness information. This effect would limit the thickness to which ice could be measured. Figure 5 shows the improvement due to initial reflection subtraction in an actual measurement of 23.75 inches of ice.

There is another fine point to the advantage of initial reflection subtraction. The attenuation due to spreading is greater for multiple time around signals than for the single time around signal. As thickness increases, the total reflection approaches the sum of the initial reflection and the single time around signal only. The remainder after initial reflection subtraction is the single time around signal, whose response is identically equal to the linear approximation. Thus the linear approximation is a better model as thickness increases. By subtracting the initial reflection, we have gone from a situation where the measurement range was sharply limited to one where the error due to the linear approximation approaches zero as thickness increases.



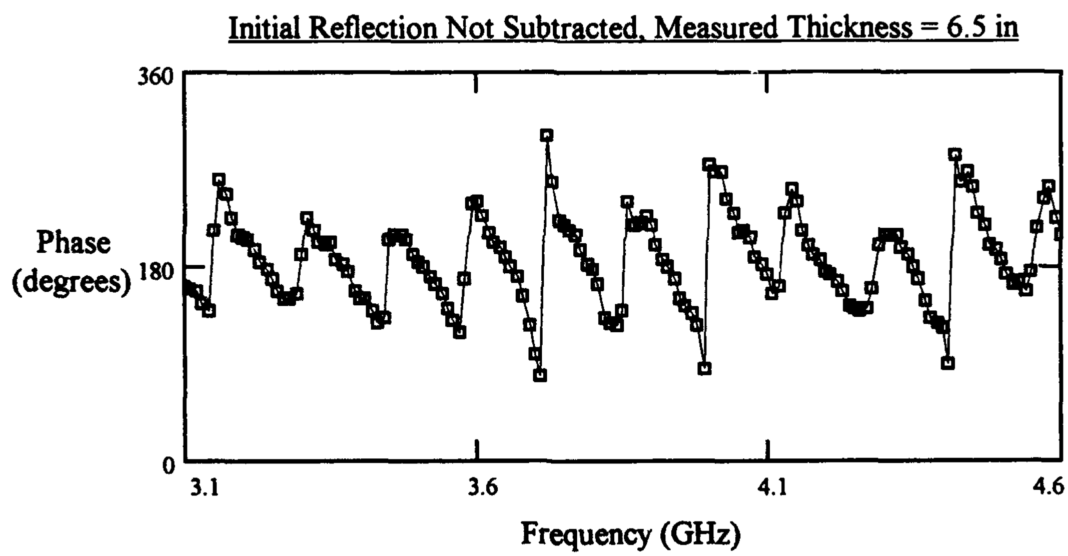


Figure 5. Illustration of Improvement in Measured Thickness by Initial Reflection Subtraction for 23.75 Inches of Ice

CALIBRATION

The procedure developed in phase I to calibrate out directivity error and frequency response error has been retained in the new approach. The calibration procedure has been expanded to include subtraction of the initial reflection off the upper ice surface. A method was developed to calibrate out error due to unwanted coupling between the ice instrument and the ice surface. The method requires measurement of an additional reference standard. These errors were found to be significant only for measurement of thin materials. The method was not included in the final ice instrument, since it would lengthen the calibration procedure and processing time, yet would not substantially improve results.

The operator has the option of calibrating or measuring ice whenever the instrument is running. The most recent calibration data is always present in memory, even if power has been turned off. Calibration and ice measurement are illustrated in figure 6. The reference measurement is accomplished by placing the instrument on a metal plate that is attached to a panel inside the case cover. The instrument is pointed into the sky to perform a background measurement. The antenna can be inverted on the metal plate as shown or it can be held for the background measurement. Finally, the antenna is shown on the ice for a thickness measurement.

HARDWARE DEVELOPMENT

Figure 7 is a top level block diagram of the ice measurement instrument. The Source assembly is a programmable synthesizer that produces radio frequency (RF) signals from 3100 to 4600 MHz in 10 MHz steps. The RF signal is routed through a circulator to the antenna and is transmitted into the ice. A portion of the RF signal is coupled off prior to the circulator for use as a reference. The reflection from the ice passes through the antenna and through the circulator to the Frequency Converter assembly. The reference is used to phase-lock a local oscillator for coherent down conversion of the received signal to an intermediate frequency (IF) of 10 MHz. The level of the IF signal is optimized for detection by varying the IF gain via program control. The signal information is then gathered by synchronous detection with the reference. Detected voltages are converted to digital form and passed to the controller for processing.

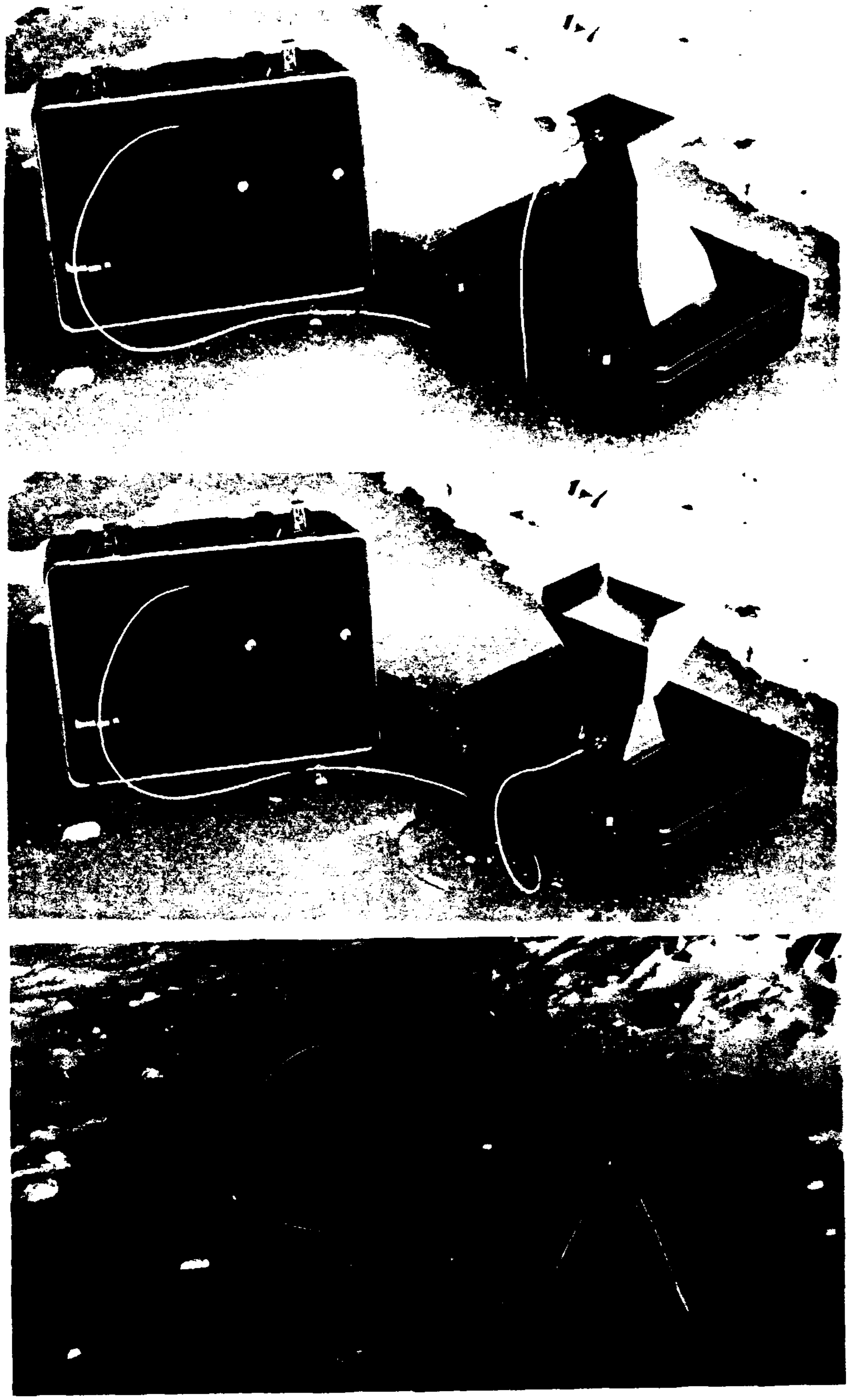


Figure 6. Metal Plate, Sky, and Ice Measurements

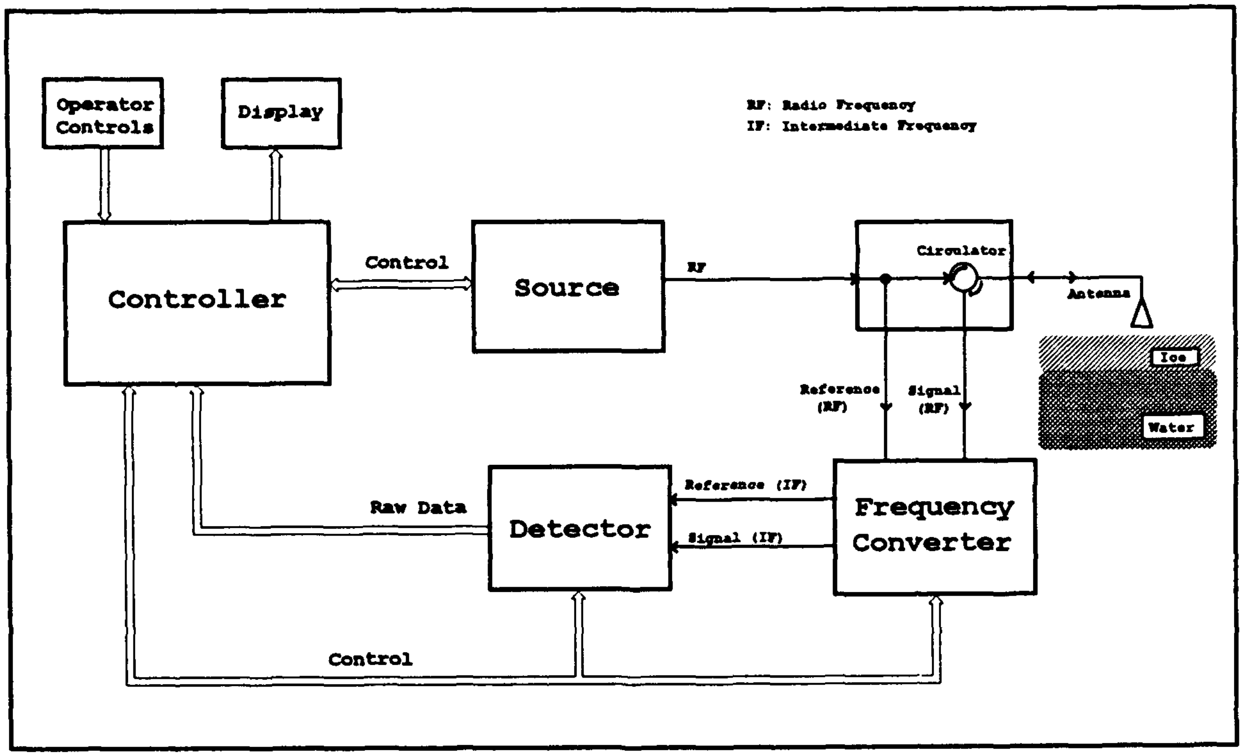


Figure 7. Top Level System Block Diagram

This process is repeated for each of the 151 frequencies in the measurement sweep. The controller directs the Source assembly to produce the next frequency. The receiver local oscillator automatically tracks the Source, maintaining the constant IF of 10 MHz. IF gain is adjusted for the received level at the new frequency. The signal is then detected, and is stored by the controller. The complete 151 point sweep is performed for each of the metal plate, sky, and ice measurements.

SECTION 4

CONCLUSION

The ice measuring instrument produced under this contract meets its goals for performance and physical characteristics. Measurement range exceeds the required 2 to 24 inches with ½ inch accuracy. Measurement time averages 12 seconds, thickness processing takes 10 seconds, and calibration is performed in under 30 seconds. The instrument is fully portable; it is powered by an internal, rechargeable battery. The instrument is built into a transit case, which also houses all accessories. Performance has been verified by measurement of ice 2 to 24 inches thick and by measurement of sheets of polyethylene 2 to 32 inches thick.

Development of the ice measuring instrument required effort in a number of disciplines: signal propagation, material measurement, near-field antenna behavior, microwave calibration techniques, system design, microwave circuit design and fabrication, signal processing, and automated system control. The development was successfully carried out entirely by personnel of Dedicated Electronics, Inc.

The ice measuring instrument requires no further development for its original application. Future efforts will thus be aimed at building on the accomplishments of this SBIR project to extend the instrument to other applications. An adaptation already in progress is to measure the permittivity of materials of known thickness, instead of measuring thickness of a material of known permittivity (ice). The intended application is measurement of the permittivity of snow. There is a simple relationship between snow permittivity and density, and in turn between density and water content. Thus an instrument that measures snow permittivity would satisfy an existing need to estimate water content in snow. Another possibility under investigation is to modify the instrument to measure thickness of glacial ice. The instrument's frequency increment and span would have to be scaled for thicknesses on the order of a kilometer. Antenna and sensitivity requirements would also have to be examined.

Other applications are based on the instrument's ability to measure reflections at microwave frequencies. Possibilities include measurement of radar absorbing material effectiveness and testing of microwave transmission lines. Finally, the experience gained during this contract in the use of antennas in the near field and in the processing and analysis of reflection data from dielectric materials will be of use for non-destructive testing and inspection. Dedicated Electronics is preparing to begin work on a contract with the U.S. Department of Agriculture to develop a means of measuring the moisture profile in wood during kiln drying.