RADAR DETECTION OF SUBGLACIAL SULFIDES

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AUTHORIZATION TO SUBMIT THESIS

This thesis of William Robert Hammond, submitted for the degree of Master of Science with a major in Geophysics and titled "Radar Detection of Subglacial Sulfides" has been reviewed in final form, as indicated by the signatures and dates given below. Permission is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

An ice radar system was used to detect sub-glacial disseminated sulfide zones beneath the Mt. Henry Clay Glacier in southeast Alaska. The sulfides, which were verified by a number of drill holes, were not detected by prior geophysical surveys. The zones were delineated by measuring lateral variations in the amplitude of radar echoes from the ice-bedrock interface at the base of the glacier. The reflected power from the disseminated sulfides ranged from 20% to 60% of the theoretically predicted reflected power from a perfect conductor at the base of the ice. The success of this experiment suggests that ice radar should be considered an important tool for direct mineral exploration in ice-covered terrain.

A low-cost portable ice-radar receiver based on a personal computer (PC) was designed and constructed for this research. The radar receiver has proved to be very versatile because the PC can control signal acquisition, display radar wave forms in near-real time, and perform sophisticated signal processing as measurements in the field. The PC-based ice-radar receiver was used for ice-thickness and bedrock power-reflection coefficient surveys of Mount Estelle Glacier in the Alaska Range of southcentral Alaska.

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This work was made possible by support from Kennecott-Alaska and Cominco Alaska and the Idaho Mining and Mineral Resources Research Institute of the College of Mines and Earth Resources, University of Idaho. I could not have completed the project without help from the following people: Ken Sprenke, my advisor and friend, who shared his wide knowledge of geophysics and the intricacies of university grantsmanship. He is a fine mentor; Scott Morris and Earl Bennett, committee members, for their constructive criticism of this thesis; Professor Maynard Miller for providing support and logistics for radar surveys on the Juneau Icefield, Alaska and review of this thesis; John Bush for advice and daily brow-beating; Ken Gordon for repairing equipment after I fixed it and for electronics help in general; Brian Jones for pulling out that consultant's contract after the first radar results looked good at Mt. Henry Clay Glacier; Lou O'Conner and Madeline Mullholland for supporting the radar surveys of Mt. Estelle glacier and then making me do IP surveys on the rock faces at the glacier in return; Doug Dodge for the spectral plot; ...and finally Carol Hammond, for reviewing the thesis, financial support, encouragement, riding herd on the kids, for her excellent technical assistance during the writing phase of this thesis and especially at the other end of the rope during the field work on Mt. Henry Clay Glacier.

DEDICATION

This thesis is dedicated to my parents who encouraged and supported my interest in science when they noted a definite lack of enthusiasm, on my part, for ranching.

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CHAPTER 1

INTRODUCTION

Problem Statement

The application and interpretation of conventional geophysical techniques in sulfide exploration are difficult in glacier-covered areas. A geophysical method designed to locate sulfide mineralization beneath glacier ice would be useful. I theorized that mono-pulse ice radar might be capable of directly detecting and delineating sulfides beneath glaciers because it is specifically designed to "see through" the ice. With the geophysical response of the ice essentially removed, the amplitude of the radar pulse reflection from the bedrock may be characteristic of the electrical parameters of the bedrock and therefore, the sulfide content. Mono-pulse ice radar has been applied to a variety of glaciological problems including ice thickness determinations (Waite and Schmidt, 1962), internal structure mapping (Harrison, 1973), ice-bedrock interface studies (Jones, 1987), glacier bed shape studies (Walford and Harper, 1981), electromagnetic parameters of ice (Jezek and others, 1978), detection of crevasses (Jezek and others, 1979), and glacier hydrology (Jacobel and Raymond, 1984). However, no one has applied mono-pulse ice radar to the detection and delineation of sulfide mineralization beneath a glacier.

It became apparent during the field work for this study that the standard method of radar data collection, using an analog oscilloscope to display radar waveforms and then recording data by photographing the oscilloscope screen, was inadequate. Several digital ice radar receiver systems have been developed but at relatively high cost and/or engineering effort (Jacobel and others, 1988; Jones and others, 1989; Wright and others, 1990).

After reviewing these existing receiver designs, I believed that less expensive commercial equipment could be used for recording digital radar waveforms and that a laptop personal computer (PC) could perform radar data acquisition and analysis in a glacial environment.

Purpose and Objectives

The purpose of this study was to investigate the theoretical and practical aspects of using mono-pulse ice radar to detect and delineate sulfide mineralization beneath a glacier. The two specific objectives were:

1. To construct a mono-pulse ice radar system and determine if radar is useful for sulfide exploration beneath a glacier by performing a field test on the Mt. Henry Clay Glacier near Haines, Alaska. This glacier was chosen because Kennecott had a drilling program on the glacier; therefore, subglacial geologic information was available for comparison with the radar results.

2. To improve the mono-pulse ice radar system by developing a low-cost PC-based digital ice radar receiver.

Literature Review

Exploration Geophysics on Glaciers

For many mineral exploration targets, the performance of commonly used geophysical methods, such as time-domain and frequency-domain electromagnetics and induced polarization, are quite adequate. However, as noted in the following examples, particular problems of subglacial sulfide detection and mapping are probably beyond the capability, resolution, and cost effectiveness of these methods.

In the case of geophysical exploration at the Mt. Henry Clay Glacier, time-domain and frequency-domain electromagnetic surveys and magnetic surveys produced no significant geophysical anomalies (Rosencrans and Jones, 1985). A DIGHEM III helicopter EM survey was carried out over the region (Dvorak, 1984). However, due to terrain clearance constraints and weather, the flight lines could not be extended to cover the Mt. Henry Clay Glacier. Later DIGHEM III surveys, commissioned by a Canadian exploration group with mining claims adjacent to and immediately across the USA-Canada border from the Mt. Henry Clay Glacier, were flown and extended to search for mineralization beneath the glacier. A broad area of lower resistivity, relative to the background values, was defined in the upper part of the glacier by this survey. Kilty stated that the DIGHEM III system would be unable to resolve individual sulfide zones of 5-15% disseminated sulfides that occur in the study area (Kilty, S., 1990: Personal communication regarding the application of DIGHEM II to mineral exploration in glacier covered terrain: DIGHEM Surveys and Processing, Inc., Missassauga, Ontario, Canada). He also noted that the DIGHEM III system, when used over glaciers, flys lower (has less "bird" clearance above the surface) than is optimal because the radar altimeter gives incorrect helicopter-surface separation data due to radar penetration into the ice. Overall, he said, the use of helicopter electromagnetic surveys in the rugged terrain usually associated with glaciers is high cost, has problems associated with terrain clearance which affect electromagnetic response from conductive features, and incomplete surveys due to poor weather are common. DIGHEM III surveys for massive sulfide horizons in the same situation would be much more likely to succeed but with weather and terrain still being dominant factors affecting survey success.

The use of surface geophysical surveys in glacier-covered terrain may also be unsatisfactory. For example, a pulse electromagnetic (Crone PEM) survey (Hrabak, 1984) done over portions of the Mt. Henry Clay Glacier encountered an extremely low geophysical response over the survey area. Interpretation of data collected with the EM system operating in a large fixed loop (Turam) mode, showed no anomalous areas beneath the glacier. Application of the same system in a coincident-loop sounding mode over the same area showed a conductive feature with a very low conductivity-thickness product, but no quantitative interpretations could be made from the data. The instrument gain was set at its maximum level and longer than normal decay-curve sampling times were used in an attempt to resolve the expected low-amplitude target response from an equally low-level half-space response generated by the glacier ice. Results from the survey were inconclusive.

The use of radar for direct detection of sulfide mineralization, whether disseminated or massive, beneath glacier ice might be an improvement over other geophysical techniques. If successful, the use of radar would enable more accurate assessment of mineral potential in glacier terrain than other conventional geophysical techniques.

The History of Ice Probing Radar

The first recorded transmission of radio waves over a long distance through ice was made at Little America Station in Antarctica in 1955 (Waite and Schmidt, 1962). Horizontal propagation of radio waves at 40 to 440 Mhz was measured between antennas separated by one mile. In 1958, Waite made the first vertical transmission of radio waves through ice at Wilkes Station in Antarctica using a 440 Mhz pulsed-type radar altimeter. High-amplitude reflections were obtained from bedrock through 600 meters of ice and corresponded with seismic soundings done at the same locations. Recognizing the limitations of radar altimeters for glaciological studies, Waite and others including Peter Evans of the Scott Polar Research Institute developed systems in the early 1960s specifically designed for ice sounding (Miller, M. M., 1990, Personal communication regarding early field tests using airborne radio-altimeter equipment on the Seward Glacier, St. Elias Mountains, Yukon Territory, Canada in 1948 under the direction of Donald Salt, University of Toronto, Canada). These ice radars operated at a center frequency of 30 to 35 MHz and displayed radar waveforms on oscilloscopes. In 1970, Gudmandsen (in Christensen, 1970) developed a more modern system operating at 60 MHz with film recording of the waveform. This class of radar system, in which a carrier frequency is switched on and off (pulsed) and a receiver is tuned to the transmitted frequency, has been used extensively on the polar glaciers of Antarctica and Greenland in ground-based and airborne configurations.

Since Waite's experiments, many different radar systems have been developed for use on polar glaciers. Only in the last 15 years have radar systems and techniques been applied to sounding temperate glaciers. Rossiter and his group (1973) may have been the first (however, see Miller, 1990) to use radio waves in studies of temperate glaciers with their 1970 experiment on Athabasca Glacier in the Canadian Rockies. They devised a radio-frequency interferometer experiment based on theoretical work done by Annan (1973) to measure in-situ electrical properties and the presence of subsurface layering in highly resistive geologic environments such as glacier ice and lunar materials. Their experiments were focused on developing background for the Surface Electrical Properties Experiment planned for the Apollo 17 lunar mission. In their experiment, five horizontal electric dipoles were laid out on the glacier surface and used to generate electromagnetic energy at 2, 4, 8, 16, and 24 MHz. Receiving antennas consisted of both coils and electric dipoles. The field strength of each frequency was recorded as the antenna moved away from the stationary transmitter. The interference pattern generated by the multi-frequency transmitter was dependent on the thickness of the glacier ice.

Goodman (1975) developed the first pulse radar system specifically for use on temperate glaciers. Tested on the Athabasca Glacier as well, Goodman's radar operated at 620 MHz with a very short pulse length and high peak pulse power and was positioned on the glacier using a VHF navigation transponder system. Due to the large bulk, the radar system was transported across the surface using a tracked over-snow vehicle. Goodman found the high frequency radar signals often scattered by bubble-ice layers and water-filled cavities but referred to the scattering as an aid to understanding englacial structure. Goodman chose the frequency of 620 MHz because components and design data were readily available (620 MHz is in the UHF television frequency band). Goodman's system also recorded radar waveforms digitally using a computer, an important advance in radar systems for glaciological studies.

Narod and Clarke (1980) developed a radar system similar to Goodman's for use in sounding the polar glaciers and ice caps of northern Canada. Their system was mounted in a helicopter and operated at a center frequency of 840 MHz but did not record waveforms digitally. Dielectric losses and internal scattering were greater than those reported by Goodman. Although successful on polar ice, the UHF radar systems' performance in penetrating temperate ice was limited due to higher attenuation and signal scattering from englacial sources.

Perhaps the most significant advancement in sounding temperate glaciers came with the development of low-frequency radar systems. Watts and England (1976) reviewed the problems associated with sounding temperate glaciers and suggested that the solution to the scattering and dielectric loss problems associated with the UHF radar systems was to reduce the transmitter frequency. From examination of the frequency dependence of the scattering bodies, thought to be water-filled voids in temperate glaciers, Watts and England found that radar reflections from the englacial scattering bodies were greatly reduced below about 10 MHz. Based on these findings, they suggested a radio-echo sounder system specifically designed for temperate glaciers. The system was to transmit a single cycle (monocycle) with a center frequency of 5 MHz and use an untuned receiver which measured field strength.

Watts and Isherwood (1978) published the design of the radio-echo sounder and demonstrated its use in determining ice thickness during gravity surveys in glacier-covered regions. The transmitter was a high-voltage pulse generator made up of transistors operating in avalanche mode. The receiver consisted of a battery-powered oscilloscope to display the radar waveforms. Identical resistively-loaded dipole antennas were used on the transmitter and receiver. The frequency of the system was easily changed by adding or removing resistively-loaded sections of the antennas. The system was very light-weight, consumed little power, and was inexpensive.

Watts and Wright (1981) made slight modifications of the surface-based radio-echo sounder system for use in airborne sounding of the heavily crevassed Columbia Glacier in Alaska. Some applications of the radio-echo sounder system to glacial problems of temperate glaciers include ice thickness measurements, glacier volume, and basal temperature studies in Peru by Jezek and Thompson (1982), englacial water movement studies in the surging Variegated Glacier, Alaska by Jacobel and Raymond (1984), ice thickness determinations for mineral exploration projects (Hammond, 1984), and ice volumes of glaciers on Cascade Range volcanoes by Driedger and Kennard (1986). No references to previous use of radar to detect sulfides beneath glaciers were found during this literature review.

Portable Digital Ice Radar Systems

Radar systems for effectively probing glacier ice have been in use since the early 1960's. Early radar systems recorded waveform data in analog form, usually on photographic film or magnetic tape and were usually carried on large sleds towed by oversnow vehicles. Recently, digital recording of radar waveforms has become feasible through advancements in high-speed digitizers and digital signal sampling techniques. The advantages of digital recording over analog methods are many. Digital waveforms can be averaged or "stacked" so that incoherent noise is reduced and the signal is enhanced. Digital waveforms can be filtered more easily and power spectra can be determined. A number of commonly used geophysical signal analysis methods can be applied to a digitally-recorded ice radar waveform.

Several groups have developed digital ice radar receivers of relatively high cost and complexity. Jacobel and others (1988) built a portable digital data-acquisition system for surface-based ice-radar studies. They founded their system on an Intel System Design Kit which uses a 8086 microprocessor supported by 4 kilobytes of RAM, 8 kilobytes of ROM, a key-pad/LED display interface, serial port, and 8255A I/O chips. The authors added a GPIB interface for data communication with the oscilloscope. Programs for setting up the oscilloscope and performing radar profiling, manual spot measurement, and automatic spot measurement tasks were written in machine-language and stored in ROM. The digitized waveform data were stored in RAM and transferred to a digital cassette tape deck at 300 baud. Radar waveform data were transferred from tape to a personal computer for analysis after the survey was completed.

Jones and others (1989) constructed a portable digital radar system which consisted of a digital radar receiver and a silicon-controlled rectifier (SCR) transmitter. Their receiver was based on a single-board microcomputer which they constructed using a GE/RCA COSMAC microprocessor. A wide-band amplifier, a sampling time-base, and an analog-to-digital converter were also designed and constructed by the authors. Digital data were recorded on a cassette tape. 50 records of 10.24 microseconds of waveform data could be stored on a single digital data cassette. Data were recovered from the receiver by dumping the cassette contents through a serial interface to another computer. A mainframe computer and programs were used to process and analyze the radar records.

Wright and others (1990) designed and built a digital profiling radar system for use in Antarctic studies. Their system consists of a digital data-acquisition system, a personal computer (IBM PC-AT), a nine-track tape driver, and a time-varying gain amplifier. The system was contained within an insulated instrumentation hut mounted on a 16-tire trailer and towed by a tracked vehicle. A fiber-optic cable was used between the transmitter and receiver to transmit both control signals and data. A LeCroy TR8818A 8-bit digitizer, capable of 100 Megasample/second, was used for high speed waveform capture and addition.

After review of these existing radar receivers, I felt that I could assemble a digital ice radar receiver by using an inexpensive computer-controlled digital-storage oscilloscope interfaced with an IBM-compatible lap-top computer.

CHAPTER 2

RADAR DETECTION OF SULFIDE MINERALIZATION

Introduction

General electromagnetic wave propagation and reflection theory is important to the application of mono-pulse ice radar to the detection and delineation of sulfide mineralization beneath glacier ice. Consideration must be given to the propagation of electromagnetic pulses through glacier ice and the electrical properties of bedrock and sulfide mineralization which make up the reflector of the electromagnetic pulses. The theoretical aspects of radio echo sounding are well covered by Bogorodsky and others (1985), and Jones (1987) specifically addresses the use of wideband electromagnetic signals in quantitative glaciological studies using radar. Discussion of electromagnetic pulse propagation and reflection in this chapter is hardware-specific, with references being made to the radar system used in this research.

Electromagnetic Wave Propagation in Glaciers

The velocity (***v***) of electromagnetic waves through ice is

$$v = \frac{c}{\sqrt{\varepsilon_r}} \qquad (1)$$

where ε_r is relative dielectric permittivity and ***c*** is the speed of light in a vacuum, 2.998 x 10^8 meters/second (e.g., Wangsness, 1979). Equation (1) may be used because glacier ice is usually non-ionized and absorption losses are low. Also by neglecting them changes ε_r by less than 0.001% (Jezek and others, 1978). Thus, the electromagnetic propagation velocity considered for ice is: v = 168.2 meters/microsecond.

The effects of surface layers on propagation velocity are an important consideration because the radar system used in this research requires the arrival time of the direct wave as a timing reference (Figure 1). Jezek and others (1978) found from radar measurement of *in situ* dielectric permittivity of glacier ice that two separate electromagnetic waves were generated from an antenna lying on the glacier surface--one wave traveling in air (called the direct wave) and one wave traveling in the ice. On a snow surface where density increases with depth (causing velocity to decrease), the wave traveling in the ice is refracted downward. The direct wave travels at the surface of the glacier at the velocity of light (300 meters per microsecond). The direct wave velocity was determined by comparing the arrival time of the direct wave with the arrival time of a signal transmitted through a 120 meter cable with known propagation delay.

<u>Electromagnetic Wave Reflection from Sulfides</u>

In order to detect sub-glacial sulfides using radar, lateral variations in the strength of bottom echoes from the ice-bedrock interface must be measurable. This variation in echo strength is similar to the seismic reflection technique of direct detection of hydrocarbon zones by noting "bright spots."

The amplitude of an ice radar bottom echo depends on the reflection coefficient, ***p***, of the ice-bedrock interface. At any interface, ***p*** is the ratio of reflected wave power to incident wave power. Theoretically, ***p*** depends on the electric properties of the two media forming the interface (Gudmandsen, 1971) and is determined by:

$$p = \left[\frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}\right]^2 \qquad (2)$$

where $\eta_k = [\ j\omega\mu_k\ (\ \sigma_k + j\omega\ \varepsilon_k\ )\ ]^{1/2}$,

ω is circular frequency,

μ_k is magnetic permeability of layer k,

σ_k is conductivity of layer k, and

ε_k is the dielectric permittivity of layer k.

j is $\sqrt{-1}$

In most earth materials, $\mu \approx 1$. If both media are good dielectrics, where $\sigma << \omega$ as in glacial ice and bedrock, $\eta_k \approx j\omega\ \varepsilon_k^{1/2}$, then ***p*** depends only on the dielectric permittivities of the two media. The relative dielectric permittivities for common earth materials are well known. Table 1 lists the

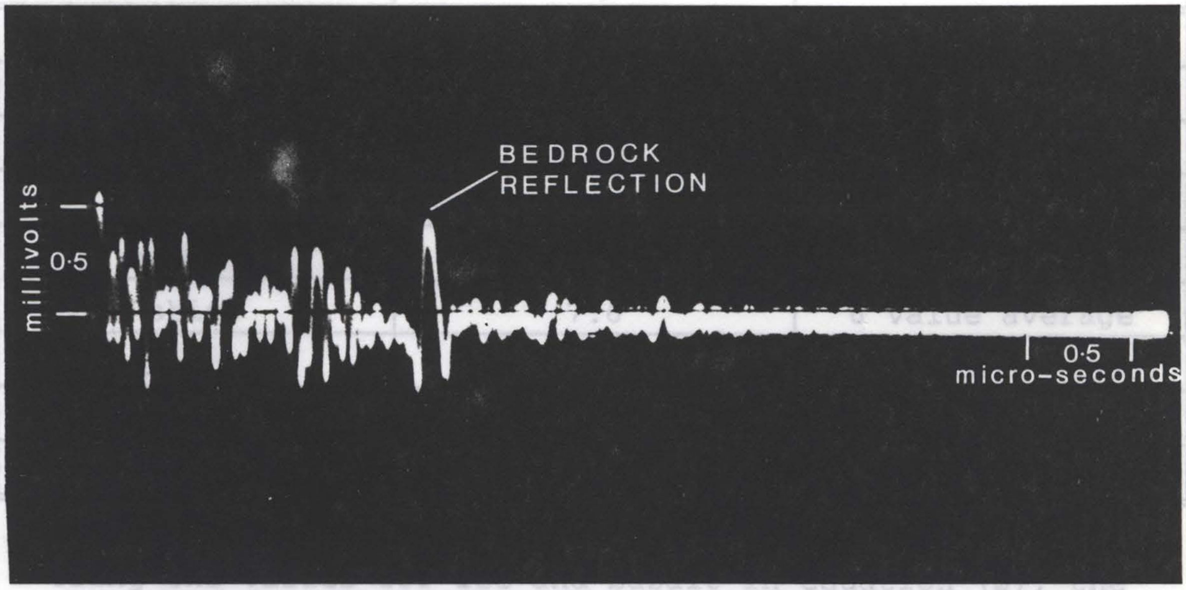

Figure 1. A representative radar trace obtained on the Mt. Henry Clay Glacier. The oscilloscope signal is triggered (on the left) by the arrival of the direct air wave. In a matter of microseconds, the reflection from the ice-bedrock interface is received.

relative dielectric permittivity of materials pertinent to this study at 1 Mhz.

Table 1: Relative Dielectric Permittivity of Selected Rocks and Minerals (from Olhoeft, 1979, 1981)

MATERIAL	ε_r	NOTE
air	88	
water	78.3	
ice	3.18	3.17 to 3.2
basalt	7.8	61 value average
andesite	7.7	5 value average
shist	7.6	6 value average
pyrite	25	see Olhoeft (1986)
sphaelerite	13.7	7.5 to 19.8
barite	13.5	9.5 to 17.4

Using the values for ice and basalt in equation (2), the predicted background value for p at the base of the Mt. Henry Clay Glacier is about 0.07.

From the above analysis, about 7% of the incident radar power will usually be reflected at the base of the glacier. However, where massive sulfide mineralization, consisting of semiconductive pyrite and chalcopyrite, is present under the glacier, the base of the ice is a boundary between a dielectric medium ($\sigma << \omega\varepsilon$) and a conductive medium ($\sigma >> \omega\varepsilon$). In this case, using equation (2), $p \approx 1$ and near total reflection of the radar energy can be expected. Thus, about 14 times more reflected power should be evident over massive sulfide mineralization than over sub-glacial non-mineralized basalt bedrock. If the sulfide mineralization is more disseminated and the sulfide grains less connected, the reflected power would be expected to be lower.

If the pyrite and chalcopyrite is completely disseminated, the mineralization may behave as a dielectric medium rather than a conductive medium at radar frequencies of 20 MHz. In this case, anomalous reflection amplitudes may still occur because the effective dielectric constant for the felsic schist will be altered by the presence of semi-conductive minerals. Olhoeft (1979, 1981), for example, noted that the density-reduced dielectric constants of dry rocks fall into a very narrow range with the exception of those that contain clay or semiconducting mineral phases such as pyrite.

Sub-glacial sulfide mineralization underlying the Mt. Henry Clay Glacier, if completely disseminated, should be capable of producing some reflected power above background levels from barren basalt. If this mineralization is more massive, up to 14 times the background level can be produced.

CHAPTER 3

RADAR SURVEYS OF THE MT. HENRY CLAY GLACIER

Introduction

The Mt. Henry Clay Glacier is located on the Canada-United States border, Skagway B-4 quadrangle, T29S, R53E and T28S, R53E, Copper River Meridian (Figure 2). Access to the area was via helicopter from the Kennecott-Alaska Exploration camp near the Pleasant Camp Customs station. The camp was located 38 miles west of Haines, Alaska, on the Haines Road.

Exploration of the area began with the discovery of placer gold on Porcupine Creek in 1898, and later placer discoveries on other creeks made the area the largest placer gold district in Southeast Alaska.

The potential for lode deposits in the district developed in 1969 when a local prospector, Merrill Palmer, discovered stratiform sulfide mineralization consisting of barite, sphalerite, and galena. Interest increased with the announcement in late 1982 of the Windy/Craggy massive sulfide discovery about 50 miles northwest in British Columbia. Southeastern Minerals and Merrill Palmer increased their exploration efforts during the 1983 field season and discovered massive sulfide boulders at the toe of the Mt. Henry Clay Glacier (Fig. 2). Anaconda, Southeastern Minerals, Kennecott-Alaska, Newmont, Cominco Alaska and others have since optioned and explored the area for economic mineral deposits.

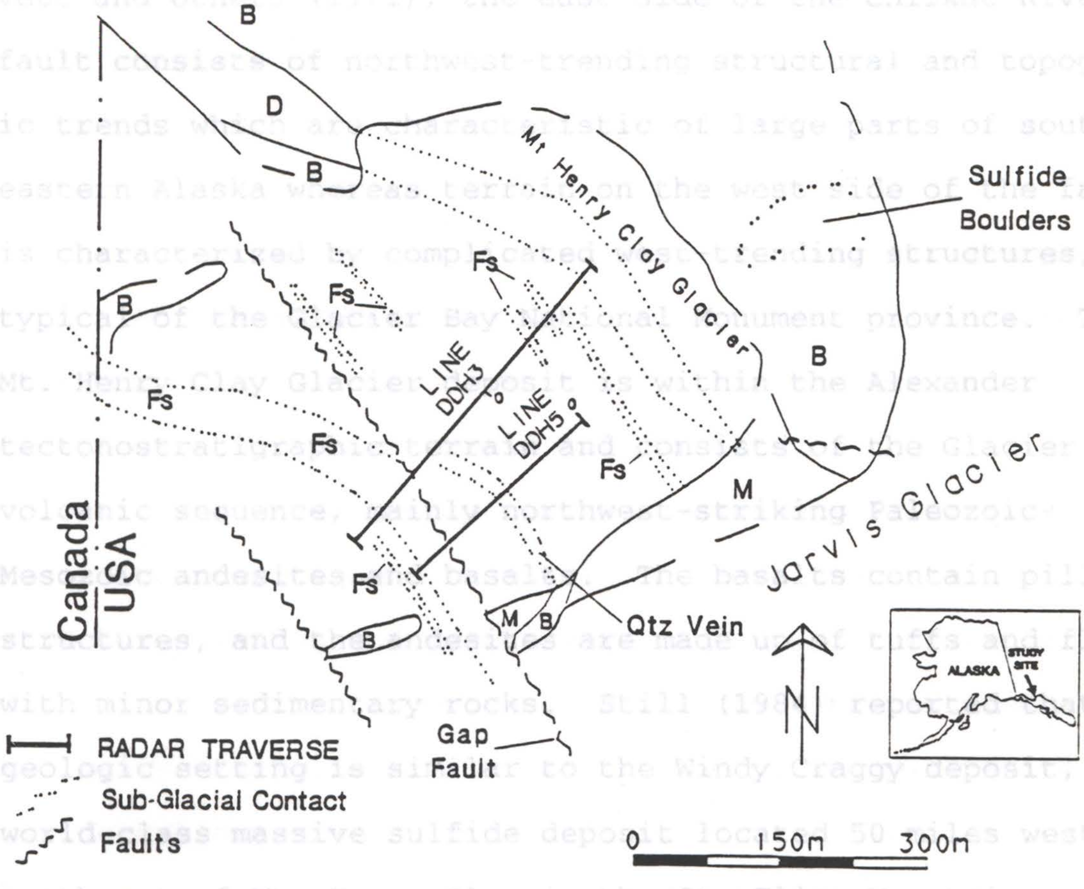

Figure 2. Location and geology of the study area. The sub-glacial geology is based on nearly 2000 meters of slant drilling. The quartz vein is sulfide bearing as are the felsic shist zones. B = basalt and andesite; D = diorite; Fs = felsic schist; M = moraine.

Regional Geology

The Mt. Henry Clay area, near Haines, Alaska, is located on the west side of the Chilkat River fault, a continuation or major branch of the Chatham Strait fault. According to MacKevett and others (1971), the east side of the Chilkat River fault consists of northwest-trending structural and topographic trends which are characteristic of large parts of southeastern Alaska whereas terrain on the west side of the fault is characterized by complicated west-trending structures, typical of the Glacier Bay National Monument province. The Mt. Henry Clay Glacier deposit is within the Alexander tectonostratigraphic terrain and consists of the Glacier Creek volcanic sequence, mainly northwest-striking Paleozoic-Mesozoic andesites and basalts. The basalts contain pillow structures, and the andesites are made up of tuffs and flows with minor sedimentary rocks. Still (1984) reported that the geologic setting is similar to the Windy Craggy deposit, a world-class massive sulfide deposit located 50 miles west-northwest of Mt. Henry Clay in the St. Elias Mountains of British Columbia.

Mt. Henry Clay Glacier Bedrock Geology

The Mt. Henry Clay Glacier deposit consists of massive sulfide boulders up to 6 feet thick that contain sphalerite, barite, pyrite, and chalcopyrite (Still, 1984). The boulders are found along a half-mile stretch at the toe of the Henry Clay Glacier. Most are rounded suggesting that they have been subjected to some fluvial erosion or spherical erosion. It might be that they were carried by the glacier to their present location. In-place ore-grade mineralization has not been found in the area. Most of the sulfide boulders assay 20% to 44% zinc, about 5% barium, several percent copper, and with trace amounts of silver and gold. Host rock for the sulfides is altered andesite containing chlorite, epidote, and phyllite. Stream sediment samples from four small subglacial streams coming out of the Mt. Henry Clay Glacier contain up to 0.11% zinc, 0.25% barium and 210 ppm copper.

Still (1984) suggested that the massive sulfide deposit may be in the bedrock beneath the ice a short distance upslope from the terminus and extend most of the width of the glacier. The basis for this interpretation is the confined area of the Mt. Henry Clay Glacier and persistence of the mineralized boulders along the 1/2 mile wide ice-front. The terminus of the glacier closely parallels the strike of the bedding. Above-background values of zinc, copper, barium, lead, silver, and gold were found in bedrock to the west and east of the glacier.

In 1984 and 1985, Kennecott-Alaska Exploration delineated, by exploratory drilling, a basalt-hosted Cu-Zn sulfide system (Rosencrans and Jones, 1985). Mineralization characteristic of a massive sulfide feeder system in basaltic rock was identified. The interpretation of their findings was that the drilling penetrated a sulfide feeder system generated in a primitive Paleozoic rift system. The drilling program failed to define any mineralization similar to the exceptional grades found in the erratic massive sulfide boulders, but disseminated Cu and/or Zn mineralization was found in all drill holes. Company geologists interpreted the limited geophysical data, the drilling results, and surface geologic mapping as indicative of an originating massive sulfide system formed in a high-energy depositional environment. They concluded that such a high energy environment could not have supported sustained euxinic (barred) basin development required for large tonnage massive sulfide mining.

Instrumentation

The radar used for the survey was based on the U.S. Geological Survey's mono-pulse radar system (Watts and England, 1976; Watts and Wright, 1981). This system consists of a transmitter, a transmitter antenna, a receiver, and a receiving antenna (Figure 3) and is described in detail in the following sections.

Transmitter

Nearly all ice radar transmitters described in the literature for use on temperate glaciers produce electromagnetic waves by generating high-voltage pulses which are applied to a

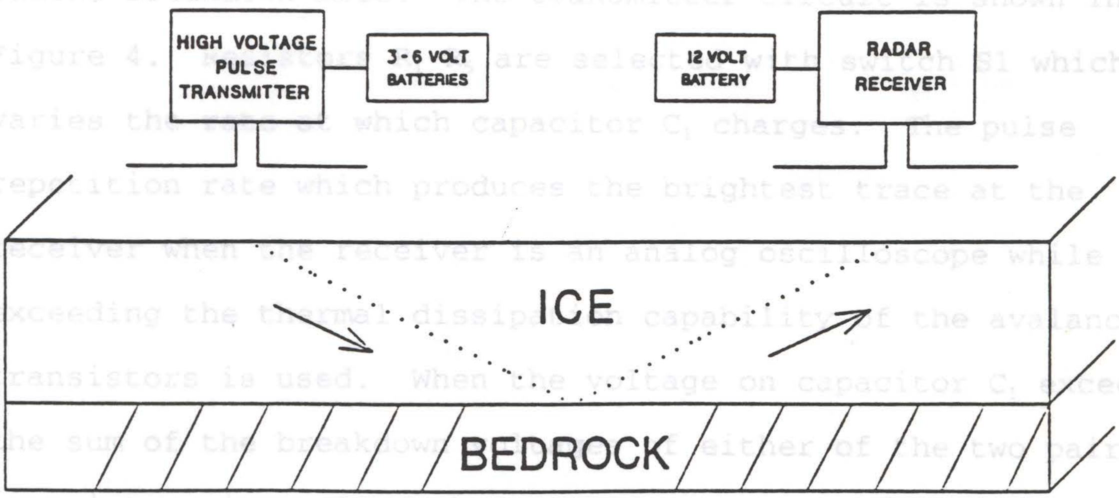

Fig. 3. Block diagram of the ice radar system.

broad-band antenna (e.g., Watts and England, 1976; Sverrisson and others 1980; Watts and Wright, 1981; Jones and others, 1989; and Wright and others, 1990). The high-voltage pulse is commonly generated by the discharge of a capacitor straight into the antenna using a high-speed solid-state switch.

The transmitter used for this study generated an output of 800-1000 volts peak-to-peak at a repetition rate of about 10 KHz through the use of bipolar transistors operating in avalanche breakdown mode. The transmitter circuit is shown in Figure 4. Resistors R_1-R_5 are selected with switch S1 which varies the rate at which capacitor C_1 charges. The pulse repetition rate which produces the brightest trace at the receiver when the receiver is an analog oscilloscope while not exceeding the thermal dissipation capability of the avalanche transistors is used. When the voltage on capacitor C_1 exceeds the sum of the breakdown voltages of either of the two pair of transistors in series, then all of the transistors switch to a conducting state from a resistive state. As long as the current from capacitor C_1 is limited by the antenna impedance (or a dummy load impedance), the transistor avalanching is non-destructive. The use of transistors in avalanche mode develops very short voltage rise-times in the order of a few nanoseconds. After capacitor C_1 has discharged into the antenna, the transistors return to their resistive state and capacitor C_1 begins recharging. The high impedance of the transistors in their non-conducting state prevents

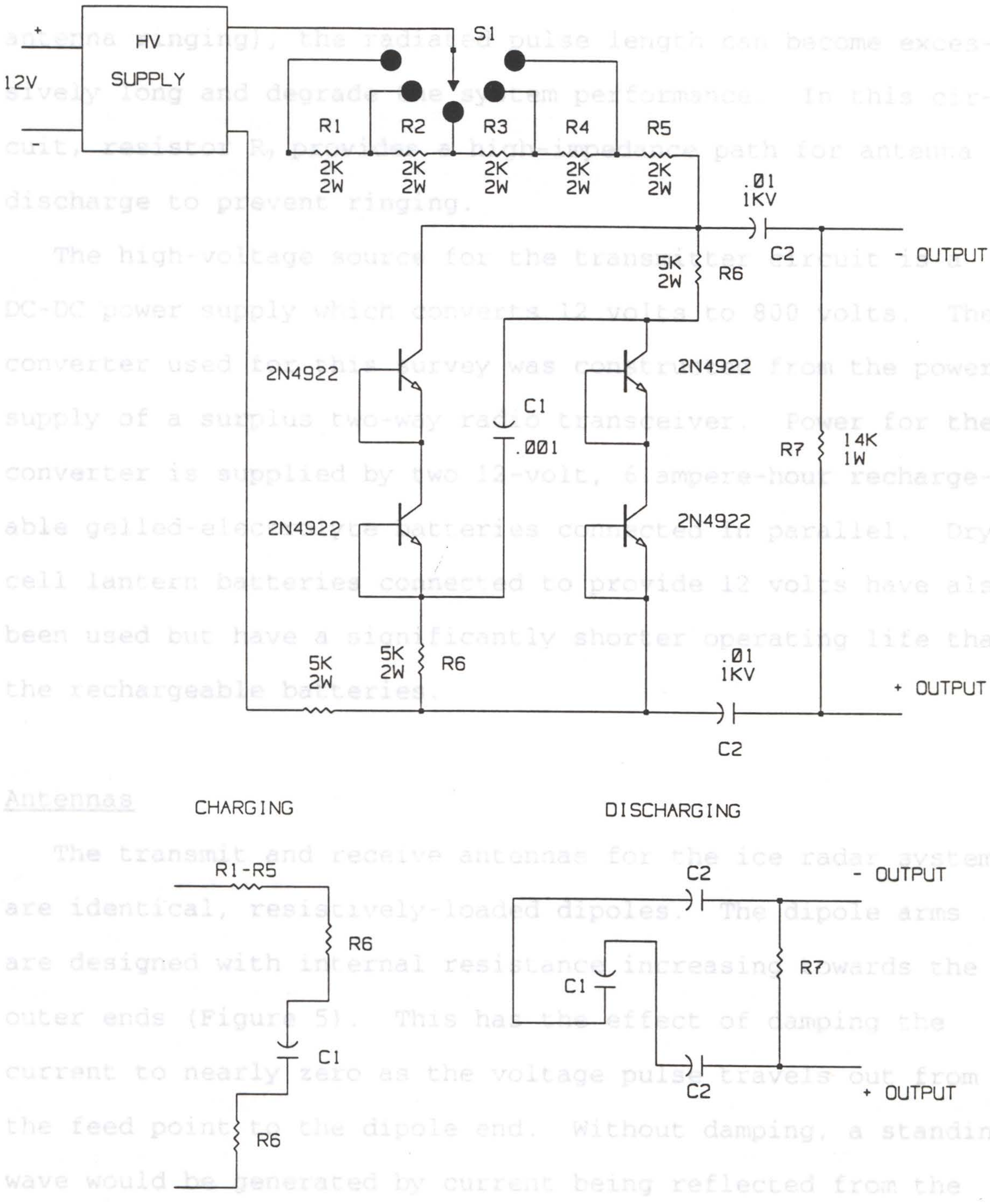

Figure 4. Schematic diagram of the ice radar transmitter (from Watts and Wright, 1981).

current from the pulsed antenna feeding back through a low-impedance path. When current does feed back through (called antenna ringing), the radiated pulse length can become excessively long and degrade the system performance. In this circuit, resistor R_7 provides a high-impedance path for antenna discharge to prevent ringing.

The high-voltage source for the transmitter circuit is a DC-DC power supply which converts 12 volts to 800 volts. The converter used for this survey was constructed from the power supply of a surplus two-way radio transceiver. Power for the converter is supplied by two 12-volt, 6 ampere-hour rechargeable gelled-electrolyte batteries connected in parallel. Dry cell lantern batteries connected to provide 12 volts have also been used but have a significantly shorter operating life than the rechargeable batteries.

<u>Antennas</u>

The transmit and receive antennas for the ice radar system are identical, resistively-loaded dipoles. The dipole arms are designed with internal resistance increasing towards the outer ends (Figure 5). This has the effect of damping the current to nearly zero as the voltage pulse travels out from the feed point to the dipole end. Without damping, a standing wave would be generated by current being reflected from the ends of the arms.

The antennas are constructed to radiate a single cycle at a center frequency determined by using

$$\upsilon = \frac{50}{h} \tag{4}$$

where h is the antenna half-length in meters and u is the frequency in MHz. The antenna approximates a half-wave dipole tuned to a frequency (f) with the wavelength $\lambda \approx 2h$; for such an antenna in this case,

$$f \approx \frac{(c/\sqrt{\varepsilon_{ice}})}{2h} \tag{5}$$

where c is the speed of light and ε_{ice} is the permittivity of ice.

The antenna is resistively loaded according to

$$R(x) = \frac{\Psi}{h - x} \tag{6}$$

where Ψ is a chosen constant in ohms, h is the antenna half-length in meters, and R is the resistance in ohm-centimeters per unit length at distance x from the feed point. Thus, the frequency is a function of the antenna length, and the resistance values needed for proper loading are independent of the antenna length. According to Hodge (1978), the constant Ψ usually has values from 100 to 500 ohms and increasing Ψ gives better resolution by shortening the pulse duration but reduces the radiated power. A value of Ψ = 500 ohms was used for radar surveys in this study based on Hodge's work where 240 meters of ice were successfully probed with Ψ = 500 ohms.

Resistively-loaded dipole antennas, in general, are designed to transmit a short pulse without ringing. If this ringing (where current oscillates between the antenna ends and the feed point) is not eliminated, the reflection from the glacier bottom may be obscured thus causing difficulties in determining an exact time for the return. An excellent discussion of resistively-loaded antenna theory and design as they pertain to use on glaciers is presented by Jones (1987). A representation of the antenna construction in shown in Figure 5.

Receiver

A Heathkit battery-operated oscilloscope with 50 MHz bandwidth was used as the receiver for the radar surveys on Mt. Henry Clay Glacier. Power for the oscilloscope was supplied by a 12 volt, 20 ampere-hour sealed lead-acid battery. Data acquisition consists of photographing the oscilloscope screen using a Nikon FM 35mm SLR camera and Polaroid self-developing 35 mm slide film, as well as manually recording the reflection times and amplitudes.

Radar Survey Field Methods

Two parallel radar survey lines were laid out perpendicular to the apparent strike of the local geology and the sulfide horizons as previously defined by Kennecott's drilling program (see Figure 2). The transmit and receive antennas were laid

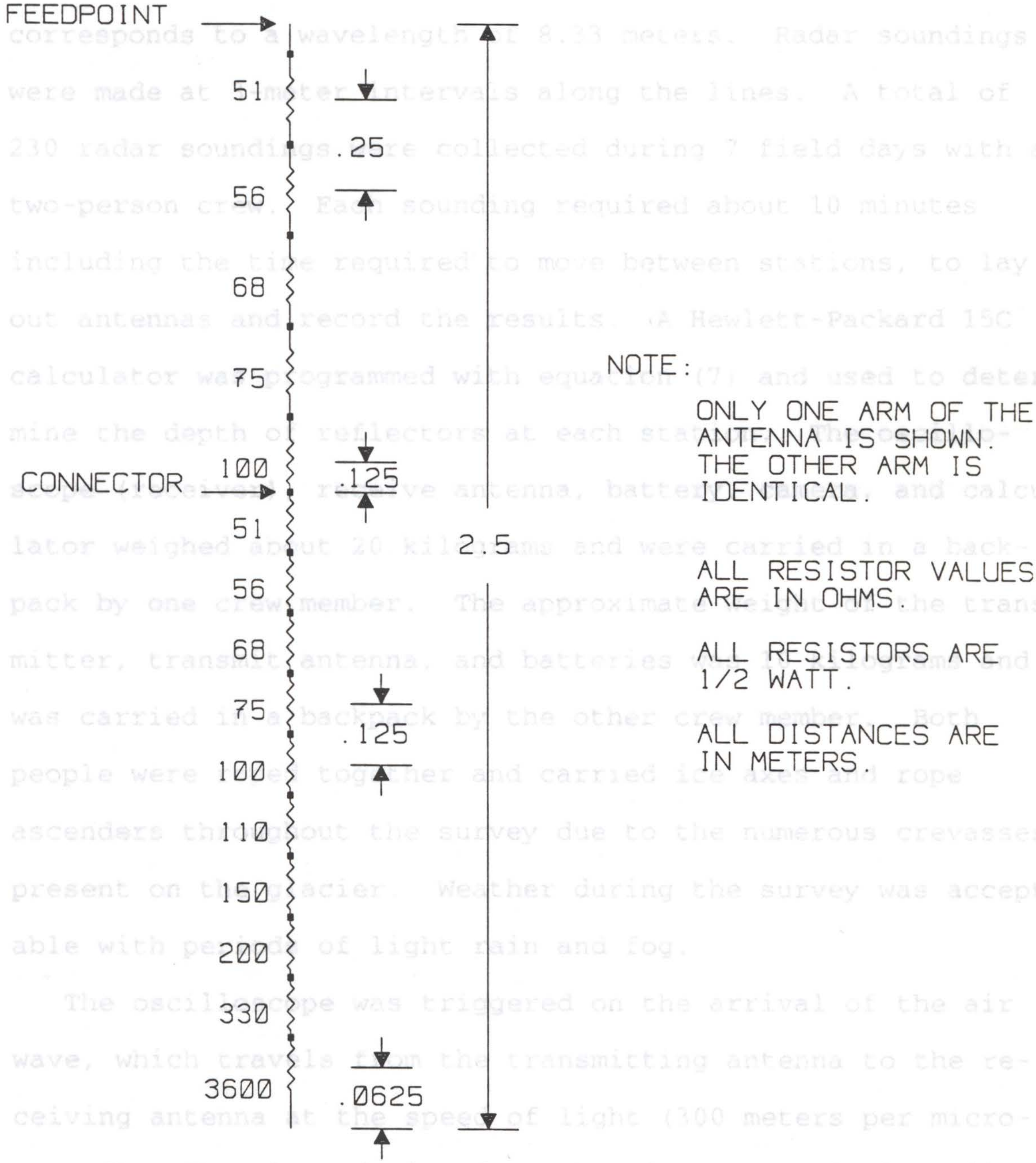

Figure 5. Antenna construction.

out parallel to each other and separated by 45 meters (the length of our climbing rope). An antenna length of 5 meters and a resultant frequency of 20 MHz was used. In ice, this corresponds to a wavelength of 8.33 meters. Radar soundings were made at 3-meter intervals along the lines. A total of 230 radar soundings were collected during 7 field days with a two-person crew. Each sounding required about 10 minutes including the time required to move between stations, to lay out antennas and record the results. A Hewlett-Packard 15C calculator was programmed with equation (7) and used to determine the depth of reflectors at each station. The oscilloscope (receiver), receive antenna, battery, camera, and calculator weighed about 20 kilograms and were carried in a backpack by one crew member. The approximate weight of the transmitter, transmit antenna, and batteries was 10 kilograms and was carried in a backpack by the other crew member. Both people were roped together and carried ice axes and rope ascenders throughout the survey due to the numerous crevasses present on the glacier. Weather during the survey was acceptable with periods of light rain and fog.

The oscilloscope was triggered on the arrival of the air wave, which travels from the transmitting antenna to the receiving antenna at the speed of light (300 meters per microsecond). The elapsed time from the air-wave arrival until the bottom reflection arrival was measured and ice thickness determined using

$$d = \sqrt{\frac{t^2v^2-x^2}{4}} \tag{7}$$

where x is the antenna separation, t is the elapsed time, and v is the wave velocity in ice, as determined by equation (1) on page 12, rewritten as follows

$$v = \frac{c}{\sqrt{e_{ice}}} = 168.2\ m/\mu s \tag{8}$$

In theory, most of the energy in the first arriving radar reflections from the ice-bedrock interface will come from all parts of the surrounding circular area on the interface that are within the first Fresnel zone which defines the zone of the majority of reflected energy. The radius of the first Fresnel zone (R_{f1}) is determined by

$$R_{f_1} = (\lambda d_{ice} + \frac{1}{4}\lambda^2)^{1/2} \tag{9}$$

where d_{ice} is the distance from the transmitter to the reflector and λ is the wavelength (Ulriksen, 1982). For the wavelength (8.33 meters) and the ice thickness (35 meters) of this survey, the radius of the first Fresnel zone was 17.6 meters. This represents the radar cross section that was sampled by each sounding. The 3-meter station spacing was therefore sufficiently close to avoid any possible spatial aliasing of signals from the base of the glacier.

The radar traces generally showed strong and impulsive bottom echoes (see Figure 1), suggesting a smooth ice-bedrock interface. In some locations, however, no reflections were obtained, probably a result of englacial scattering by large englacial voids or water-filled conduits or holes in the ice, as previously noted. The arrival times of the bottom echoes showed that the ice thickness varied smoothly from 30 meters to 40 meters in the area of the radar survey.

The raw bottom echo amplitudes (in millivolts, peak to peak), were squared for comparison with theoretical power reflection coefficients. The final results are shown in Figure 6 along with sub-glacial geology as determined from drill holes. Radar data from the Mt. Henry Clay Glacier survey are listed in Appendix B.

Radar Survey Results

The radar survey results indicating changes in echo strength show five anomalous zones which correlate very well with the known changes in mineralogic character of the sub-glacial geology (Figure 6). Three of the anomalous zones correspond with sub-glacial occurrences of sulfide-bearing felsic schists. The remaining two anomalous zones correspond with a thick quartz vein containing barite and chalcopyrite exposed at the glacier edge. The reflection power in the anomalous zones ranges from 3 to 7 times the background value, or a ratio from 20% to 60% of the predicted value for a perfect bedrock conductor. This suggests that the anomalies, if associated with mineralization, are due to disseminated rather than massive sulfides; an interpretation borne out by the drill hole analysis.

The radar survey results are strictly empirical and the apparent spatial correlation of the radar anomalies with sulfide occurrence, although good, could be influenced by other causes. It is possible, for example, that the sulfide zones could be relatively resistant to erosion and have smoother, or more specular, surfaces for radar reflection compared to surrounding country rock. At the other extreme, the sulfide zones may have been more weathered than surrounding rocks and have crevices filled with free water which could explain higher reflectance of the radar signal. Considering these alternatives, however, on the Mt. Henry Clay Glacier, if the reflections are truly related to the sulfides, I contend from the information in this study that the relationship is probably direct. On adjoining exposed bedrock, the felsic schist host rock is less resistant to erosion than the basalt-andesite country rock. Also it is probably significant that very little free water was encountered at or below the ice-bedrock interface during drilling.

Discussion

The Mt. Henry Clay Glacier experiment indicates that ice radar may be a useful tool for mapping disseminated sulfide deposits buried under glacial ice. In fact, radar may be the

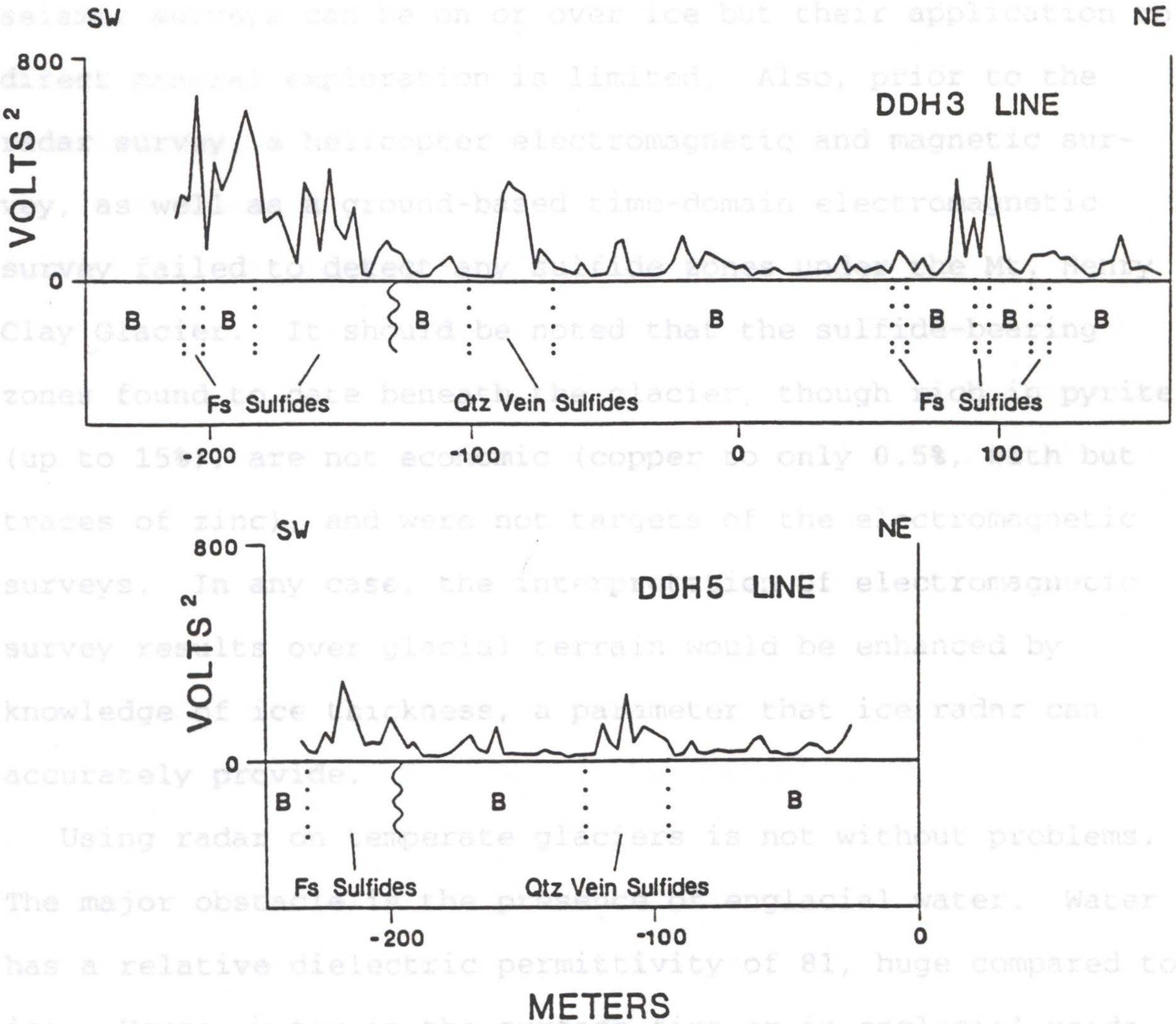

Fig. 6. Radar bottom echo strength and drill hole results on the Mt. Henry Clay Glacier. The echo strength plotted is the squared peak-to-peak amplitude. See Figure 2 for line locations and a plan view of sub-glacial geology. B = basalt and andesite; Fs = felsic schist.

only geophysical tool capable of accomplishing this task. Ice, an excellent insulator, precludes the use of conventional resistivity or induced polarization surveys. Gravity and seismic surveys can be on or over ice but their application to direct mineral exploration is limited. Also, prior to the radar survey, a helicopter electromagnetic and magnetic survey, as well as a ground-based time-domain electromagnetic survey failed to detect any sulfide zones under the Mt. Henry Clay Glacier. It should be noted that the sulfide-bearing zones found to date beneath the glacier, though rich in pyrite (up to 15%), are not economic (copper to only 0.5%, with but traces of zinc), and were not targets of the electromagnetic surveys. In any case, the interpretation of electromagnetic survey results over glacial terrain would be enhanced by knowledge of ice thickness, a parameter that ice radar can accurately provide.

Using radar on temperate glaciers is not without problems. The major obstacle is the presence of englacial water. Water has a relative dielectric permittivity of 81, huge compared to ice. Hence, water in the surface firn or in englacial voids can scatter radar transmissions. On glaciers in which free water is a problem, using radar frequencies of 8 MHz or less can minimize the scattering (Watts and England, 1976). However, decreasing the radar frequency also increases the radius of the first Fresnel zone. Thus, the ability to detect narrow sulfide zones beneath glaciers with much free water may be limited.

Generally, the colder or more polar a glacier is, the less free water will be present (Miller, 1976), and the scattering problem will be less severe. For example, on another temperate glacier with copious englacial water in 1988, I was unable to detect bedrock reflections through more than 120 meters of ice. This was during radar surveys of the Taku Glacier near Juneau, Alaska; however, radar surveys of the Icy Basin area, a branch of the Taku Glacier, recorded strong bedrock reflections through about 460 meters of ice. Again, the difference in radar penetration in these two cases could have been due to varying englacial water content.

Glacial till present at the base of a glacier could also complicate radar surveys for mineral exploration. A thick zone of till present at the base of a glacier may preclude sulfide detection by masking subtle changes in the bedrock reflection coefficient. Dowdeswell and others (1984) noted the problems associated with interpretation of radar data from basal till layers. On the Taku Glacier, Poulter (see Miller, 1949) found evidence of a basal till zone between the ice and bedrock in areas with ice thickness of 300 to 500 meters during seismic surveys. Drewry (1975) presented a comparison of radar and seismic methods for glaciological studies which dicusses basal till layers. Also, Jones (1987) modelled electromagnetic wave reflection from a variety of glacier bed materials. His data suggest that by strictly using radar any accurate determination of rock content of thin layers at the base of a glacier would be difficult. His modelling results suggest that noticeable effects seen in synthetic radar pulses occur only for till layers in excess of 3 meters in thickness and for rock concentrations of more than 35 percent by volume. Jones further reminded us that such thick layers are not uncommon in glaciers and therefore that the possibility of subglacial detritus layers must be considered when interpreting radar data.

CHAPTER 5

A PC-BASED ICE RADAR RECEIVER

Introduction

The radar experiment on the Mt. Henry Clay Glacier suffered in that data were recorded in analog form. One disadvantage was that the results could not be displayed as one would a seismic reflection section. A somewhat practical design for a portable digital ice radar exists (Jones and others, 1989). Digital capability greatly enhances an ice radar survey because it makes it possible to process radar traces in the same manner as seismic data. In surveys like the present study, in which subtle amplitude variations are critical, modern digital data processing techniques would have been very useful.

In order to take advantage of digital recording and processing of ice radar data, a low-cost digital receiver was developed for subsequent field use, using the lessons learned from the Mt. Henry Clay investigation (Hammond and Sprenke, 1990). A block diagram of an ice-radar system using such a personal computer (PC)-based receiver is shown in Figure 7. Technical specifications for the receiver are given in Appendix A. The receiver uses an IBM-compatible laptop computer interfaced with a computer-controlled digital storage oscilloscope. The computer acquires the radar waveforms, displays and processes the signals, and stores them on disk. Software allows waveform stacking and measurement of time, voltage, and

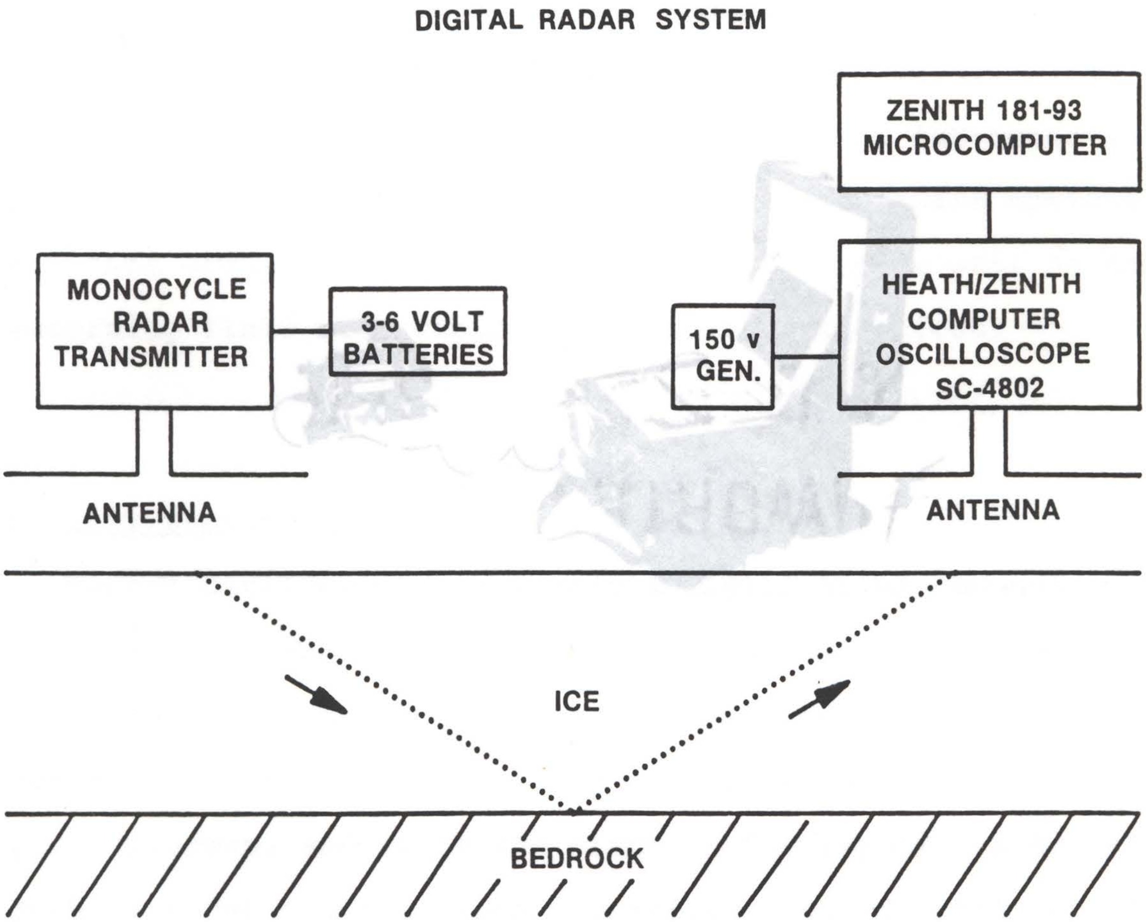

Fig. 7. A block diagram of an ice-radar system including the PC-based ice-radar receiver.

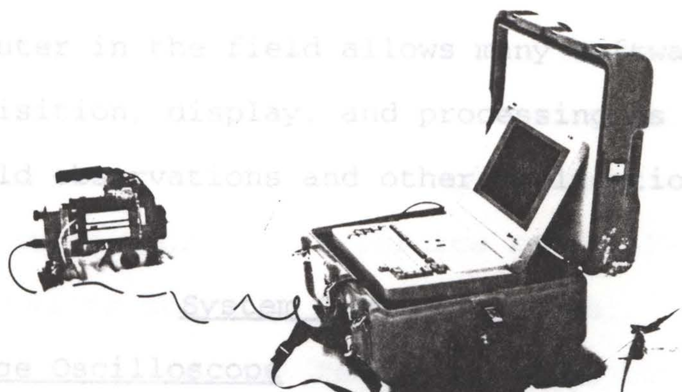

Fig. 8. The PC-based ice-radar receiver in operation on the Mt. Estelle glacier, Alaska.

frequency. The total weight of the packframe-mounted receiver including generator and insulated container is 22 kilograms (Figure 8). This system is less complicated to assemble than other portable digitally-recording ice radar receivers (Jacobel and others, 1988; Jones and others, 1989). Because commercial components are used and no custom engineering effort is required, the system is inexpensive. The total cost, including laptop computer, is less than $2000. The system is versatile because the presence of an IBM-compatible personal computer in the field allows many software options for data acquisition, display, and processing as well as for recording field observations and other applications.

System Components

Digital Storage Oscilloscope

Recent developments in waveform digitization technology have led to inexpensive computer-controlled oscilloscopes. These devices interface with a personal computer through a serial port or logic buss and use computer software to display, process, and store the signal. For repetitive signals, such as radar transmissions and reflections, digital oscilloscopes can achieve very short sampling intervals by using equivalent time sampling. This means that only one sample is taken each time the oscilloscope is triggered. This is not a serious limitation for the ice radar system used in this study because the radar transmitter produces 10,000 pulses per second. Therefore, an entire 512 point waveform can be acquired in 52 milliseconds.

The Heath SC-4802 Computer Oscilloscope was chosen as the waveform digitizer in the digital radar receiver mainly because it can be used with any IBM-compatible personal computer (including lap top computers) with a standard RS232C serial interface. All other computer oscilloscopes require the installation of an internal expansion card in the personal computer. Most laptops are incapable of housing expansion cards. The Heath unit has several additional characteristics that make it suitable for use in an ice radar receiver:

1. The oscilloscope accurately samples radar waveforms in the frequency range appropriate for ice radar (1-20 MHz) at a sampling interval as short as 0.2 nanoseconds.

2. The unit has a vertical resolution of 8 bits (1 part in 256), a value comparable to the best analog oscilloscope screens.

3. The sampling circuits can be reached only by signals below 100 MHz. Thus, alias-free measurements can be assured simply by using a sampling interval of less than 5 nanoseconds.

4. The record length is 512 digital samples, sufficient for many ice radar applications.

5. The unit allows interactive cursor measurements of time and voltage, thus allowing accurate determination of reflection times and amplitudes in the field.

6. The instrument, which draws 48 watts at 110 volts AC, can be powered by a very lightweight AC/DC generator or can be modified for use with batteries.

7. The oscilloscope costs less than $300.

A limitation of the Heath computer oscilloscope is that it does not contain a delay line. This means that some data immediately after the trigger point will be lost. According to the manufacturer, the amount of lost data depends on the sampling interval: at a 4 nanosecond sampling interval, 345 nanoseconds of data are lost; at a 0.2 nanosecond sampling interval, 80 nanoseconds of data are lost. These values were verified by the manufacturers laboratory tests.

Laptop Personal Computer

The computer oscilloscope interfaces directly with a laptop personal computer through a RS-232C serial interface. A Zenith 181-93 laptop computer was selected for this study because it has a rugged plastic case, two 9 centimeter (3.5 inch) 720-kilobyte floppy disk drives, a socket for an Intel 8087 math coprocessor, a lid which completely covers the disk drives and the keyboard when closed, a large 80 character by 25 line backlit liquid crystal display capable of color graphic adapter (CGA) operation, and the capability to operate from a 12 volt D.C. source. However, any battery-powered IBM-compatible computer with a RS-232C serial interface, CGA screen, and floppy drives could be used. The computer screen

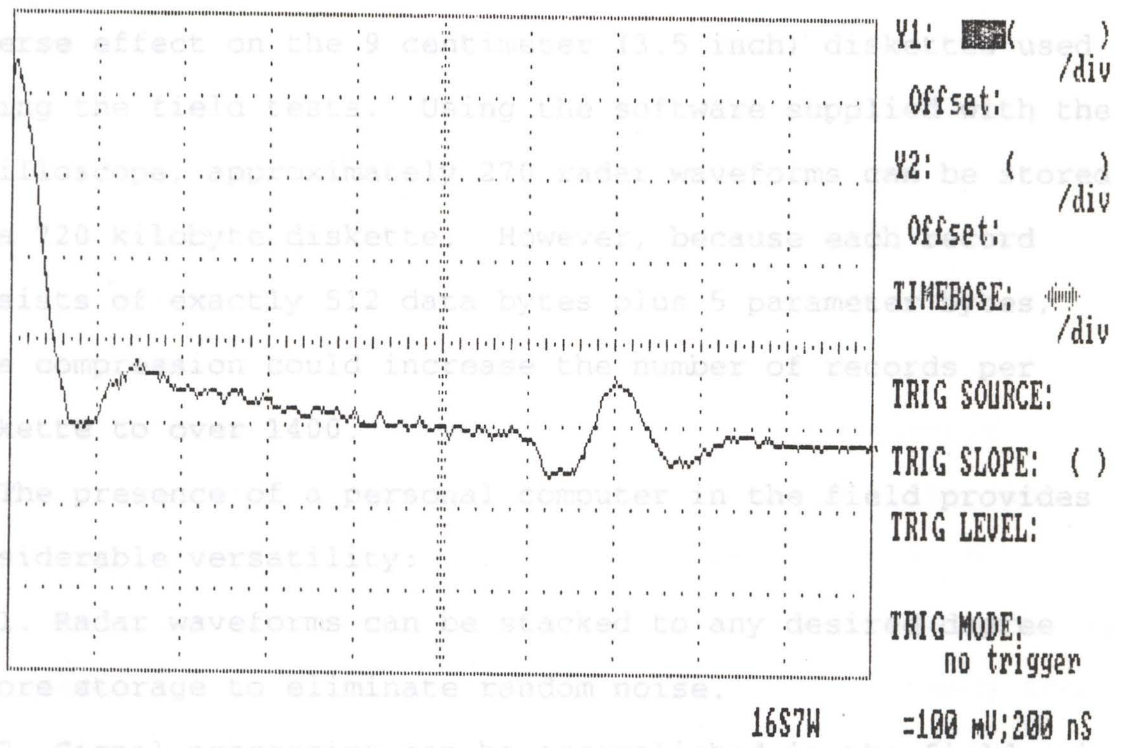

Fig. 9. An example of the computer oscilloscope display showing a radar waveform and data collection parameters.

functions as the oscilloscope display in the field and radar waveforms can be viewed in near real time as they are collected (Figure 9). The digitized waveforms along with oscilloscope parameters are stored as files on floppy disks. Although other researchers have reported problems with floppy disks in the field, temperatures of 2-3 degrees Celsius had no adverse effect on the 9 centimeter (3.5 inch) diskettes used during the field tests. Using the software supplied with the oscilloscope, approximately 270 radar waveforms can be stored on a 720 kilobyte diskette. However, because each record consists of exactly 512 data bytes plus 5 parameter bytes, data compression could increase the number of records per diskette to over 1400.

The presence of a personal computer in the field provides considerable versatility:

1. Radar waveforms can be stacked to any desired degree before storage to eliminate random noise.

2. Signal processing can be accomplished in the field using a wide variety of existing software for IBM-compatible computers or custom software written in a common high-level programming language.

3. Previously collected waveforms and cross-sections can be displayed at any time.

4. The operator can use the computer to record field observations and survey information.

5. Positioning equipment (GPS, LORAN-C) can be interfaced to the computer to provide geographic coordinates of radar survey measurements.

Field Test

The receiver was successfully tested on the Mt. Estelle Glacier in the central Alaska Range of Alaska. Approximately 150 radar soundings were made to determine the ice thickness of the glacier and to attempt to map power reflection coefficients of the ice-bedrock interface (Hammond, 1988). The radar transmitter and antennas described in Chapter 3 were used with the antennas deployed in the broadside parallel mode. A frequency of 1.25 MHz was used for the surveys; however, spectral analysis of a typical bedrock reflection indicated reflection peak power at 2.86 MHz (Figure 10). The waveform stacking feature of the oscilloscope software package was useful for eliminating radio-frequency interference from the generator, other geophysical equipment in operation, and FM radio transmissions. Air temperatures of 2-3 degrees Celsius did not adversely affect operation of either the computer or the oscilloscope. Light precipitation fell during one period but was dealt with by shielding the open computer and oscilloscope with a plastic sheet.

The radar records along a bottom-echo profile at the test site were 2 microseconds in length and were digitally sampled at a 4 nanosecond interval (Figure 11). Although the oscillo-

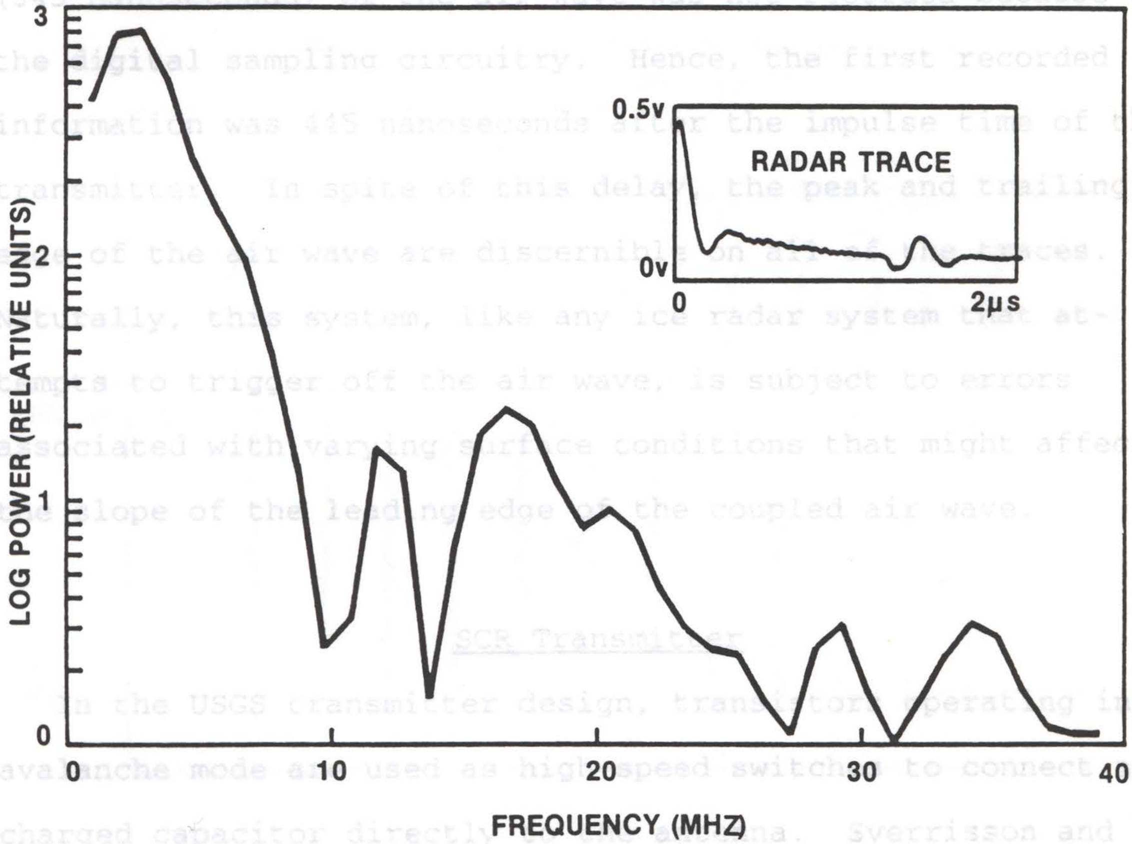

Fig. 10. A typical digital waveform recorded on the Mt. Estelle Glacier, Alaska, and its power spectrum. The PC-based receiver allows the use of a wide variety of standard signal analysis software in the field.

scope triggered on the onset of the air wave at the receiving antenna, zero time on the traces was set at the impulse time of the transmitter. This is done by assuming a 100 nanosecond delay between transmitter impulse time and the onset of the air wave at the receiver 30 meters away. The leading edge (345 nanoseconds) of the air wave was not recorded because of the digital sampling circuitry. Hence, the first recorded information was 445 nanoseconds after the impulse time of the transmitter. In spite of this delay, the peak and trailing edge of the air wave are discernible on all of the traces. Naturally, this system, like any ice radar system that attempts to trigger off the air wave, is subject to errors associated with varying surface conditions that might affect the slope of the leading edge of the coupled air wave.

SCR Transmitter

In the USGS transmitter design, transistors operating in avalanche mode are used as high-speed switches to connect a charged capacitor directly to the antenna. Sverrisson and others (1980) described a transmitter using a silicon-controlled rectifier (SCR) as the switch. Although the rise time of SCR-based transmitters is generally slower than avalanche transistor transmitters, the benefits are reduced power consumption, greater efficiency, better circuit reliability, and a clean output pulse. Because of difficulties during construction and operation of the avalanche-transistor transmit-

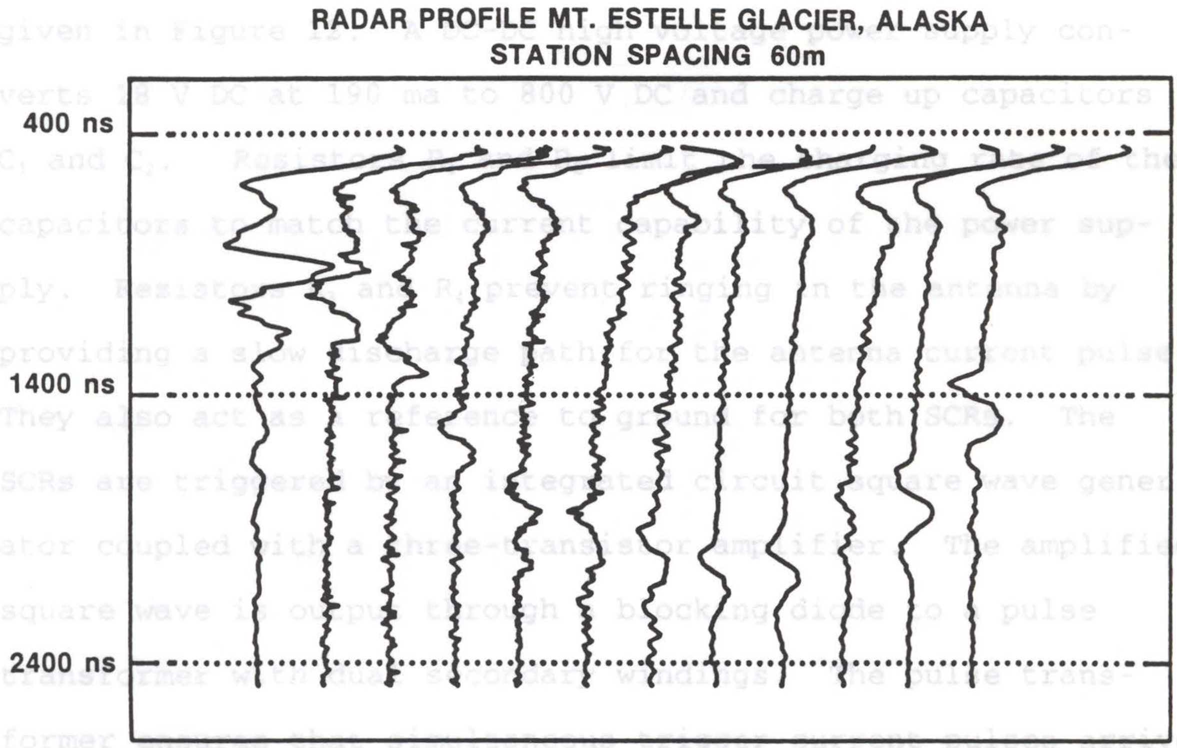

Fig. 11. An ice-radar profile across the Mt. Estelle Glacier as recorded using the PC-based receiver.

ter used for Mt. Henry Clay Glacier radar surveys, a SCR-based radar transmitter was constructed for use during the Mt. Estelle Glacier radar surveys.

Based on a design reported by Jones (1987), the SCR transmitter was constructed with the addition of a circuit to control the pulse repetition rate. The schematic of this is given in Figure 12. A DC-DC high voltage power supply converts 18 V DC at 190 ma to 800 V DC and charge up capacitors C_1 and C_2. Resistors R_1 and R_2 limit the charging rate of the capacitors to match the current capability of the power supply. Resistors R_3 and R_4 prevent ringing in the antenna by providing a slow discharge path for the antenna current pulse. They also act as a reference to ground for both SCRs. The SCRs are triggered by an integrated circuit square wave generator coupled with a three-transistor amplifier. The amplified square wave is output through a blocking diode to a pulse transformer with dual secondary windings. The pulse transformer ensures that simultaneous trigger current pulses arrive at each SCR gate. Resistor R_5 and R_6 are adjusted so that the trigger current is appropriate for each SCR, and thus simultaneous triggering occurs.

When the SCRs are triggered by a current pulse to their gates, the capacitors are discharged through the SCRs into the antenna. One half of the antenna receives a 800 V positive pulse and the other half receives a 800 V negative pulse. Thus, a 1600 V peak-to-peak pulse is presented to the antenna

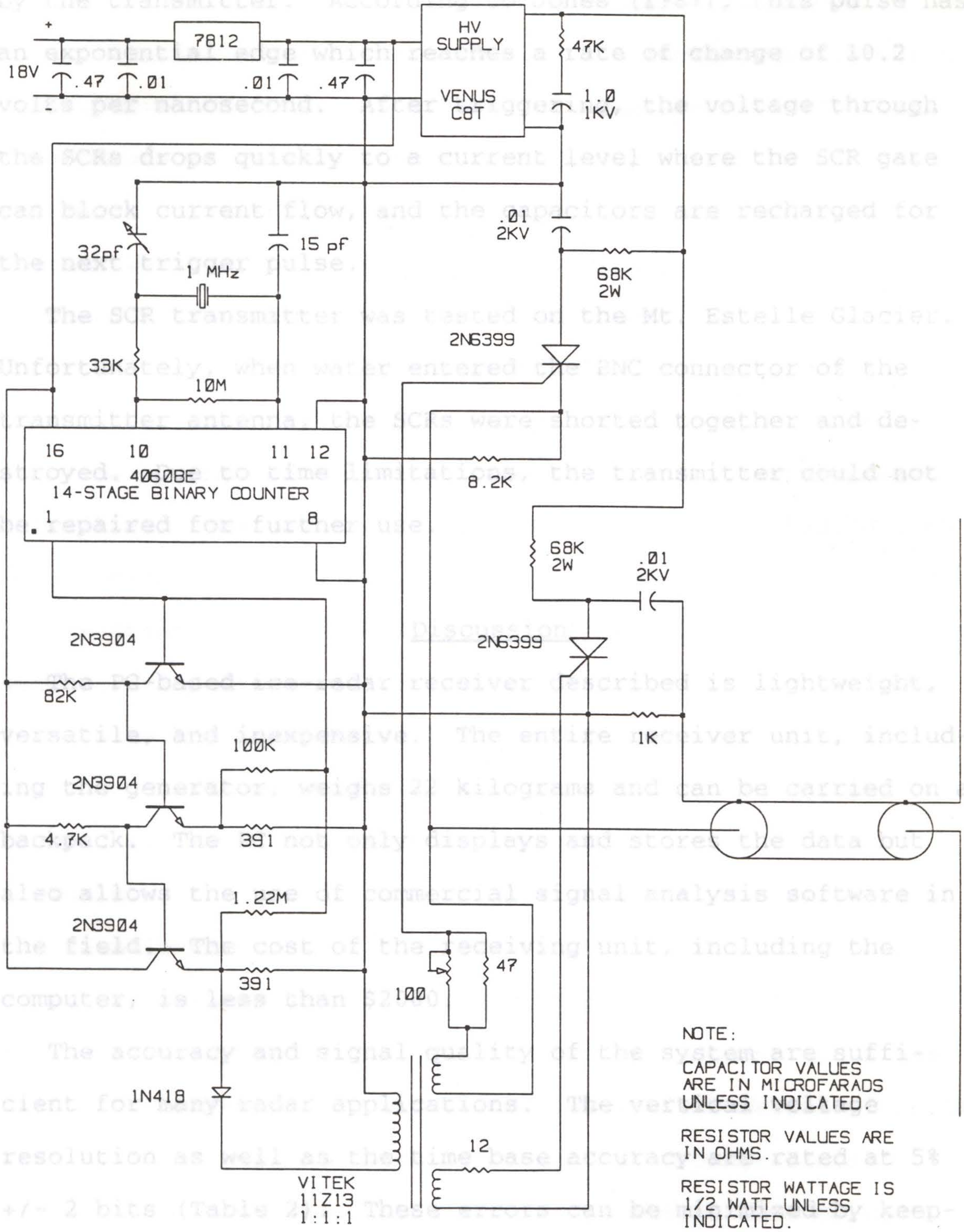

Fig. 12. Schematic diagram of the SCR transmitter.

by the transmitter. According to Jones (1987), this pulse has an exponential edge which reaches a rate of change of 10.2 volts per nanosecond. After triggering, the voltage through the SCRs drops quickly to a current level where the SCR gate can block current flow, and the capacitors are recharged for the next trigger pulse.

The SCR transmitter was tested on the Mt. Estelle Glacier. Unfortunately, when water entered the BNC connector of the transmitter antenna, the SCRs were shorted together and destroyed. Due to time limitations, the transmitter could not be repaired for further use.

Discussion

The PC-based ice-radar receiver described is lightweight, versatile, and inexpensive. The entire receiver unit, including the generator, weighs 22 kilograms and can be carried on a backpack. The PC not only displays and stores the data but also allows the use of commercial signal analysis software in the field. The cost of the receiving unit, including the computer, is less than $2000.

The accuracy and signal quality of the system are sufficient for many radar applications. The vertical voltage resolution as well as the time base accuracy are rated at 5% +/-2 bits (Table 2). These errors can be minimized by keeping the displayed waveform as large as possible on the screen. Because random noise can be reduced by averaging, the system is capable of producing very clean records. The traces in Figure 11, for example, were stacked 50 times. The digitizing error, which includes the effects of power supply variations, temperature variations, temperature-induced gain variations, and input noise is limited, according to the manufacturer, to the two least significant bits. Two bits out of 256 bits represents less than a 1 % error due to digitizing noise.

The major problem with the system is the loss of data immediately after the trigger point. This problem could be overcome by the addition of a commercially-available video delay line. The receiving antenna would be connected to both input channels of the oscilloscope and the delay line placed on one channel. The air wave would trigger the oscilloscope and the delay line could be adjusted to show the entire waveform including pre-trigger information. Possible errors associated with varying slopes on the leading edge of the coupled air wave could then be evaluated.

The use of a long length of coaxial cable as a delay line has been investigated. RG 174/U coaxial cable with a propagation velocity factor of 66% of the speed of light and an attenuation factor of 3.2 decibels per 100 meters length was used. To achieve a 400 nanosecond delay, 79.2 meters of cable were coiled and placed within the digital storage oscilloscope. Tests performed with a pulse generator show correct delay times but also show some distortion of the pulse waveform. This distortion is most likely due to inductive effects of the coiled cable.

A high-performance version of the Heath digital storage oscilloscope, the Heath SDS-5000, has a pre-trigger capability which would eliminate need for a delay line. However, this instrument consists of two internal expansion boards designed to be installed within a desk-top computer chassis. A laptop computer with two full-size PC XT/AT expansion slots or an expansion chassis would be required to use the SDS5000.

Although completely adequate results were obtained at 2-3 degrees Celsius, operation of the radar receiver in harsher and colder glacial environments needs further evaluation. Technically, the specified minimum operating temperature of the computer and oscilloscope is 10 degrees Celsius. However, discussions with the manufacturers suggest that adequate performance should be obtainable to much lower temperatures provided that the liquid-crystal display on the computer doesn't freeze. A laptop computer with a shock-mounted hard disk drive and gas plasma display, especially designed for harsh environments and cold temperatures, would improve the radar receiver. However, existing laptop computers which meet these criteria cost nearly $10,000.

The SCR transmitter constructed for the Mt. Estelle Glacier survey failed on the first try due to liquid water present in the antenna connector. The water caused the SCR switches to short to ground and damaged them. Due to limited field time, the SCR transmitter could not be repaired and tested again.

Laboratory testing of the transmitter indicated that a symmetrical high voltage pulse is produced by the SCR circuit, unlike the noisy, assymetrical pulse produced by the USGS transistor transmitter.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A mono-pulse ice radar system has been used to estimate the location of sulfides in bedrock beneath the Mt. Henry Clay Glacier. Time-domain electromagnetic surveys and airborne electromagnetic surveys carried out prior to the radar surveys were unable to resolve the question of the presence of disseminated sulfides. The relative reflection coefficient changes measured by the radar surveys of Mt. Henry Clay Glacier correlate well with disseminated sulfides as delineated through drilling, indicating that radar may be a significant exploration tool in glacier-covered areas for disseminated metal deposits (Hammond and Sprenke, 1991).

A portable PC-based ice-radar receiver was assembled at a cost of approximately $2000, and field tested on the Mount Estelle Glacier in the Alaska Range of southcentral Alaska. The PC-based radar receiver proved to be a significant improvement over an analog oscilloscope. Because the computing capabilities of the PC are available in the field, signal acquisition variables can be controlled and radar waveform parameters can be easily measured in near-real time. Also, radar waveforms can be recorded in digital form, which allows for easier presentation of radar data and is necessary for performing signal processing.

Recommendations

Dielectric permittivity of the minerals forming the radar reflector is the key electrical property that affects radar response. Unfortunately, published values for relative dielectric permittivity of rocks and minerals are only available up to 1 MHz; therefore, measurements at 20 MHz (the frequency used during the radar surveys) should be made. However, it may not be possible to perform *in situ* measurements of the relative dielectric constant of the sub-glacial sulfide-bearing bedrock at the ice-bedrock interface. Laboratory measurements on core samples obtained by Kennecott's drilling could have been done as part of this study, but the values derived would not have been representative of the properties of the weathered sulfides and bedrock present at the ice-bedrock interface. A special effort would have had to be made to intercept the sulfides at the ice-bedrock interface.

Digital signal processing techniques may help in resolving bedrock reflections. Spectral analysis of radar reflections may yield more definitive information on the electrical properties of the ice-bedrock interface and therefore the sulfide content of the bedrock. Phase relations between the transmitted wave and the reflected wave should be investigated to determine if there is phase shift over sulfides. Digital recording of waveforms is imperative if more than semi-quantitative analysis is to be done on the radar data.

The hand-wired USGS radar transmitter used for the surveys was found to be somewhat unreliable in the field. A printed circuit board for the transmitter should be constructed to improve reliability.

Evaluation of the SCR transmitter has yet to be completed; however, laboratory tests and reports from other users indicate that the transmitter should perform better than the avalanche-transistor transmitter.

The analog oscilloscope has been superseded by a PC-based digital oscilloscope capable of digital recording of waveform data on floppy disk. Improvements to the digital receiver should include the use of non-volatile solid-state random access memory as the recording medium, the use of a gas plasma display instead of a liquid crystal display, and a sealed membrane keyboard, features which would enhance the cold weather capabilities of the system. A delay line is needed in the receiver so that pre-trigger waveform data can be recorded for analysis. The addition of a satellite navigation receiver to the digital radar receiver would provide accurate data collection site locations.

Finally, it should be noted that the high quality of the radar data from Mt. Henry Clay Glacier is partly due to the purposeful oversampling, conducive local conditions were also an important factor. Englacial and basal till layers commonly found in glaciers were not present. Also the ice is not only shallow ice (under 100 meters in the areas investigated) but because of the relatively high elevation (1700 meters) it may be inferred to have an internal sub-tropical to sub-polar thermal regime; i.e. below freezing throughout, thus minimizing radar wave attenuation through the absence of much liquid water. Glaciothermally warmer and deeper glaciers which overlie sulfide deposits also need to be surveyed if we are to fully evaluate the use of radar as a valid mineral exploration tool.

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APPENDIX A

RECEIVER SPECIFICATIONS

Model Number	Heath SC4802/4850
Input impedance	1 m-ohm
Total voltage gain	125
Attenuator	29 steps in 1-2-5 sequence
Vertical sensitivity	5 millivolts per division
Vertical accuracy	5% +/- 2 bits
Amplitude resolution	8 bits
Bandwidth	2 Hz to greater than 90 MHz
Time to gather one record	52 milliseconds
Time to store one record	10 seconds
Number of samples per record	512
Time base accuracy	5 % +/- 2 bits
Sampling interval	200 picoseconds minimum
CPU and CPU clock speed	80C88, 8 MHz (computer) Z80, 4 MHz (oscilloscope)
Memory	640 kilobytes of RAM
Inputs/outputs	Computer keyboard 640 X 200 pixel LCD (backlit) two 3.5 inch disk drives RS232C serial interface 2-channel oscilloscope inputs
Software attributes	Waveform stacking (1-250 stacks) Cursor measurement of wave-form attributes waveform comparison (memory)
Power requirements	48 watts at 110 VAC (scope). 12.6 watts at 18 VDC (PC).
Power supply	Tanaka QEG-300 generator 300 watts at 120 VAC 120 watts at 12 VDC
Weight	22 kilograms

APPENDIX B

MT. HENRY CLAY GLACIER RADAR DATA

Station numbers (SN) are distance in feet from the DDH-3 drill hole collar: - indicates upglacier, + indicates downglacier. Reflection amplitudes (RA) are in millivolts, peak-to-peak. No reading (nr) indicates no bedrock reflection detected.

RADAR SURVEY LINE DDH3

SN	RA	SN	RA	SN	RA
-690	15	-240	11	210	8
-680	18	-230	8	220	4
-670	17	-220	6	230	8
-660	26	-210	5.5	240	3
-650	10	-200	5	250	2.5
-640	21	-190	8.5	260	8
-630	18	-180	3	270	19
-620	nr	-170	4	280	8
-610	22.5	-160	5	290	15
-600	25	-150	11	300	8
-590	22	-140	12	310	20.5
-580	14	-130	5	320	15.5
-570	15	-120	3	330	8
-560	16	-110	4	340	5.5
-550	11.5	-100	4	350	3.5
-540	7	-90	5	360	9
-530	19	-80	8	370	9
-520	17	-70	12.5	380	8.75
-510	10	-60	nr	390	10

RADAR SURVEY LINE DDH3 (continued)

SN	RA	SN	RA	SN	RA
-500	20	-50	5.5	400	8
-490	14.5	-40	10	410	8
-480	12	-30	9	420	6
-470	16.5	-20	8	430	2.5
-460	5	-10	nr	440	4
-450	4.5	0 (DDH3)	6	450	7
-440	10	10	7	460	8
-430	12	20	2	470	12.5
-420	10	30	5	480	5
-410	9.5	40	4.75	490	nr
-400	5	50	6	500	6
-390	4	60	3	510	nr
-380	5	70	4	520	3
-370	7	80	3.5		
-360	8	90	4.5		
-350	9.5	100	4.5		
-340	5	110	4.5		
-330	3.5	120	5		
-320	3	130	9		
-310	3	140	3		
-300	3	150	7		
-290	17.5	160	4		
-280	19	170	5		
-270	18	180	7		
-260	17.5	190	2		
-250	5.5	200	10		

RADAR SURVEY LINE DDH5

SA	RA	SA	RA	SA	RA
0 (DDH5)	nr	-270	4.5	-540	6
-10	nr	-280	8	-550	9.5
-20	nr	-290	4	-560	7.75
-30	nr	-300	2	-570	6
-40	nr	-310	8	-580	4.5
-50	nr	-320	9	-590	3
-60	nr	-330	10	-600	3.5
-70	nr	-340	11	-610	2.5
-80	11	-350	7.5	-620	8
-90	8	-360	15.5	-630	6
-100	5	-370	5.5	-640	10
-110	4	-380	8	-650	12.5
-120	6.5	-390	11.5	-660	7.5
-130	7.5	-400	4	-670	8
-140	5	-410	4	-680	7
-150	3.5	-420	3.9	-690	9
-160	3	-430	2	-700	13
-170	4.5	-440	4.2	-710	17
-180	4	-450	4.5	-720	7.5
-190	9	-460	6	-730	10
-200	8	-470	4	-740	4
-210	5	-480	4	-750	5
-220	5	-490	4	-760	8
-230	4.5	-500	4.5		
-240	5	-510	4		
-250	5.5	-520	11		
-260	4	-530	4.5		