

## INSTRUMENTS AND METHODS

### RADIO-ECHO EQUIPMENT FOR DEPTH SOUNDING OF TEMPERATE GLACIERS

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**ABSTRACT.** Radio echo-sounding equipment has been designed, and used for depth sounding on temperate glaciers in Iceland. Two devices have been built. *Mark I* operates in the frequency band 2 to 5 MHz. The overall range is 100 to 1 000 m. The arrival of the echo can be timed with an accuracy which corresponds to 20 m resolution. The equipment has been used for routine soundings on Mýrdalsjökull and Vatnajökull for the last two years. *Mark II* operates at 2 to 10 MHz. The range is from 30 to 400 m and the range resolution is 8 m. The equipment has been used for successful soundings on valley glaciers.

The power consumption of the whole system is 18 W plus 72 W for the oscilloscope (Tektronix Model 465). The voltage is supplied from 12 V car batteries. The total weight of the equipment is about 35 kg plus the weight of batteries. The antennae are contained in 16 mm plastic tubes. The equipment is placed on two sledges and towed behind a snowmobile or a skidoo. A continuous sounding record is photographed from the oscilloscope.

**RÉSUMÉ.** Équipement à écho-radio pour sondages de profondeur des glaciers tempérés. Un équipement pour sondages par écho-radio a été conçu et utilisé pour des sondages de profondeur sur glaciers tempérés en Islande. Deux appareils ont été construits. *Mark I* opère à des fréquences de 2 à 5 MHz. Sa gamme de profondeurs explorées va de 100 à 1 000 m. Le retour de l'écho peut être saisi avec une précision qui correspond à une résolution de 20 m. Cet équipement a été utilisé pour des sondages de routine sur les glaciers Mýrdalsjökull et Vatnajökull ces deux dernières années. *Mark II* opère entre 2 et 10 MHz. La gamme explorée est de 30 à 400 m et sa résolution de 8 m. L'équipement a été utilisé avec succès pour des sondages de glaciers de vallée.

La consommation en énergie de tout le système est de 18 W plus 72 W pour l'oscilloscope (Modèle Tektronix 465). La tension est fournie par des batteries de voiture de 12 V. Le poids total de l'équipement est d'environ 35 kg en plus du poids des batteries. Les antennes sont contenues dans des tubes plastiques de 16 mm. L'équipement est placé sur deux traineaux et tracté derrière un véhicule toute neige ou un scooter des neiges. Un enregistrement continu du sondage est photographié depuis l'oscilloscope.

**ZUSAMMENFASSUNG.** Radar-Echoausrüstung für Tiefenmessungen auf temperierten Gletschern. Es wurde eine Radar-Echoausrüstung entwickelt und zur Tiefenmessung auf temperierten Gletschern in Island benützt. Zwei Vorrichtungen wurden gebaut: *Mark I* arbeitet im Frequenzband von 2 bis 5 MHz. Die Reichweite beträgt 100 bis 1 000 m. Die Echoankunft kann zeitlich mit einer Genauigkeit festgestellt werden, die einem Auflösungsvermögen von 20 m entspricht. Die Ausrüstung wurde in den beiden letzten Jahren für Routine-messungen am Mýrdalsjökull und am Vatnajökull benützt. *Mark II* arbeitet mit 2 bis 10 MHz. Die Reichweite beträgt 30 bis 400 m mit einer Auflösung von 8 m. Die Ausrüstung wurde erfolgreich für Messungen auf Talgletschern benützt.

Der Energiebedarf des gesamten Systems beträgt 18 W, zuzüglich 72 W für das Oszilloskop (Tektronix Modell 465). Der Strom wird aus 12 V-Autobatterien entnommen. Das Gesamtgewicht der Ausrüstung liegt bei 35 kg, zuzüglich des Batteriegewichtes. Die Antennen befinden sich in 16 mm-Plastikröhren. Die Ausrüstung wird auf zwei Schlitten verladen und hinter einem Schneemobil oder Skidoo gezogen. Die kontinuierliche Anzeige des Oszilloskopes wird photographisch festgehalten.

#### INTRODUCTION

The present report describes radio echo-sounding equipment for use on temperate glaciers. The equipment has been designed and built at the Raunvísindastofnun Háskólans (the Science Institute of the University of Iceland).

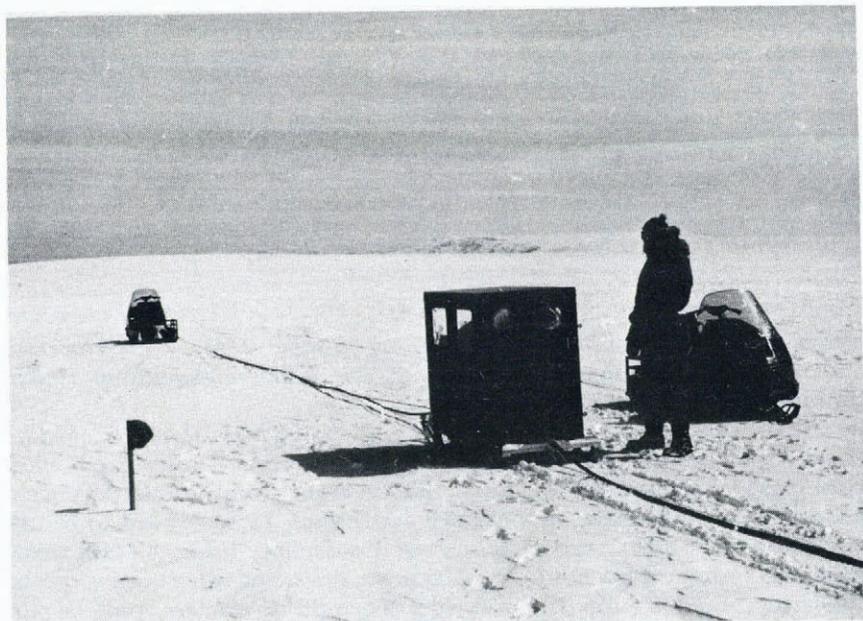
For the last 10–15 years radio echo-sounding with 30–60 MHz signal frequency has been successful on Arctic glaciers in Greenland and Antarctica (Bailey and others, 1964; Gudmandsen, 1969; Evans and Smith, 1969). But several attempts to use the same technique on temperate glaciers (Goodman, 1970; Smith and Evans, 1972) proved to be unsuccessful until Watts and others (1975) reported successful soundings using 5 MHz frequency. A description of the equipment has not been published. Watts and others (1975) explained that the problem encountered in radio echo-sounding of temperate glaciers could be attributed to water-filled voids in the ice. Watts and England (1976) analysed the total scattering cross-section of water-filled voids in the ice as a function of frequency. The results suggested that

sounding at frequencies below 8 MHz would eliminate or greatly reduce the total return power due to scattering and it might be possible to penetrate thick temperate ice (1 000 m) and still get a good ratio of bottom return to scattered return.

Following the success of Watts and others (1975) a joint British-Icelandic expedition carried out radio echo-sounding experiments on Vatnajökull (Björnsson and others, 1977). The experimental instrument was built at Cambridge University (Ferrari and others, 1976). After the tests on Vatnajökull in 1976 the equipment was designed and built at the Science Institute. Further development during the last two years has resulted in the design of two devices—Mark I and Mark II. Mark I operates in the frequency band 2 to 5 MHz. The overall range is from 100 m to 1 000 m, which is required to encompass the ice thicknesses expected on ice caps in Iceland. This equipment has been used for routine soundings on the ice caps Vatnajökull and Mýrdalsjökull. A preliminary map of the topography under Mýrdalsjökull and a profile across western Vatnajökull have been published (Björnsson, 1977). Further, the Grímsvötn and the Bárðarbunga areas in Vatnajökull have been mapped in details (paper in preparation by H. Björnsson). Mark II operates at 2 to 10 MHz and has a range from 30 m to 400 m. The device was designed for use on valley glaciers and outlets from the large ice caps, and has been tested on Tungnárjökull and the valley glacier Gljúfurárjökull, north Iceland, during the summer of 1978. Further, Mark II has been used for routine soundings of Storglaciären, Isfallsglaciären, and Rabotsglaciären in Swedish Lapland in March–April 1979.

#### RADIO ECHO-SOUNDING EQUIPMENT

The radio echo-sounding system consists of a transmitter, a receiver, and two antennae. In the present system, the transmitter and the receiver together with 12 V car accumulators are mounted on two sledges. Each sledge was placed at the centre of an antenna. The antennae were towed on a line behind a skidoo as seen in Figure 1. A bicycle wheel is mounted



*Fig. 1. Radio echo-sounding at Vatnajökull. A skidoo is towing the device. The receiver sledge with a hut for the operator is placed at the centre of the receiver antenna.*

on the transmitter sledge and a built-in a.c. generator generates pulses which ensure that the repetition rate of the transmitter is proportional to the speed at which the sledge is running. The distance travelled along the glacier surface is obtained by integrating in the receiver the repetition rate of the transmitter. The altitude of the glacier surface can be recorded by a barometric altimeter. A barograph which records continuously at the base camp is used to calibrate the barometric altimeter. The receiver is connected to an oscilloscope with a camera for  $Z$ -mode (intensity modulation) recording. Figure 2 shows typical  $Z$ -mode pictures. The glacier surface is seen in the upper half of the picture and the bottom return in the lower half.

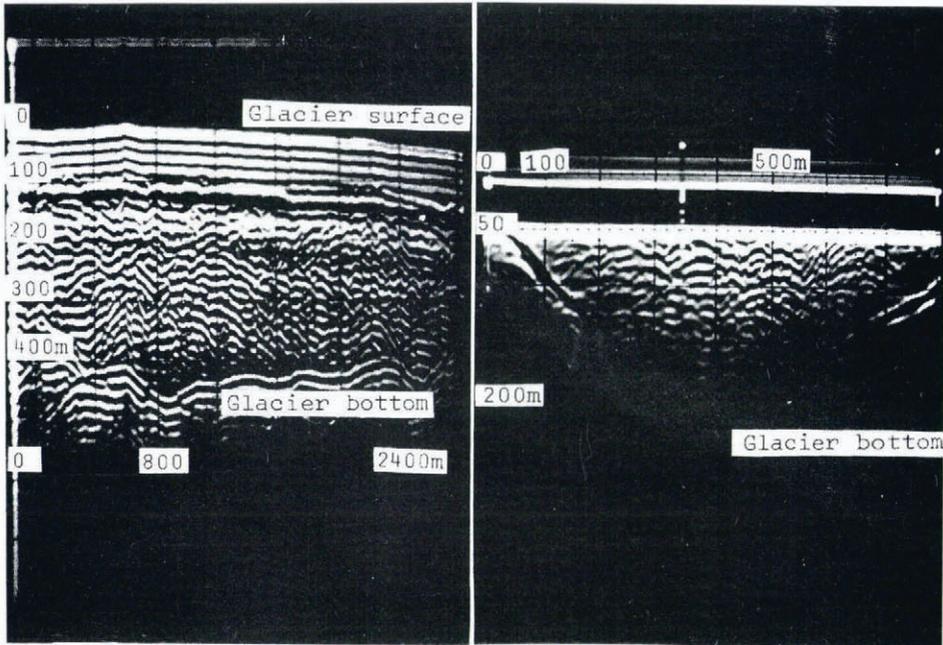


Fig. 2.  $Z$ -mode film records. Continuous records along the line of echoes. (a) A record of Mark I from Grímsvötn, Vatnajökull;  $\alpha = 0.1$  for the antenna. The ringing phenomenon visible in the record is due to the fact that the signal is band-limited. (b) A record of Mark II from Storglaciären, Sweden;  $\alpha = 1.0$  for the antenna.

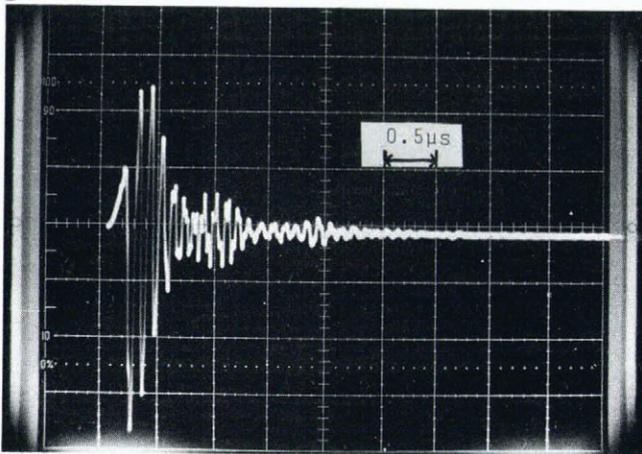


Fig. 3. A-mode film record from the valley glacier Gjúfurarjökull, north Iceland. The transmitted pulse, internal reflections, and the pulse reflected from the bedrock can all be identified.

The  $X$ -axis shows the distance travelled along the glacier surface. The  $Y$ -axis shows the elevation of the glacier surface and the height of the underlying bedrock above sea-level. The white vertical lines on the  $Z$ -mode picture are due to interference from short-wave radio stations.

The  $A$ -scope (signal versus time) representation is used to monitor the output signal from the receiver. Figure 3 shows a typical  $A$ -mode picture.

The main characteristics of the equipment are summarized in Table I.

TABLE I. CHARACTERISTICS OF THE RADIO ECHO-SOUNDING EQUIPMENT

	<i>Transmitter Mark I</i>
Frequency	2 to 5 MHz
Peak pulse power	8 kW or 69 dBm
Repetition rate	0 to 1 300 Hz, proportional to the speed of the transmitter sledge
Antenna	Broad-band half-wave dipole, resonance frequency 3.8 MHz
Antenna gain	Approximately -10 dB
Pulse width	0.8 $\mu$ s
Power consumption	12 W at maximum repetition rate. Proportional to the repetition rate
Dimensions	25 cm $\times$ 25 cm $\times$ 40 cm
Weight without batteries	6 kg
	<i>Transmitter Mark II</i>
Frequency	2 to 10 MHz
Peak pulse power	8 kW or 69 dBm
Repetition rate	Similar to Mark I
Antenna	Broad-band half-wave dipole, resonance frequency 8.1 MHz
Antenna gain	Approximately -10 dB
Pulse width	0.1 $\mu$ s
Power consumption	The same as for Mark I
Dimensions and weight	Similar to Mark I
	<i>Receiver (Mark I and Mark II)</i>
Antenna	Same type as for the transmitter
Sensitivity	-81 dBm for 0 dB S/N output
Noise level	+12 dB above thermal
Band-width	0.1 to 10 MHz without BP filter. 2 to 5 MHz with BP filter
Overload recovery time	100 nS without filter
Power consumption	6 W + 72 W for the Tektronix Model 465 oscilloscope
Dimensions	25 cm $\times$ 25 cm $\times$ 40 cm. The oscilloscope is 25 cm $\times$ 40 cm $\times$ 70 cm with camera
Weight without batteries	8 kg. The oscilloscope weight is 15 kg
	<i>System</i>
System performance	150 dB excluding antennas
Minimum range	100 m for the Mark I transmitter. 30 m for the Mark II transmitter
Range resolution	20 m for the Mark I transmitter. 8 m for the Mark II transmitter
	The arrival of an echo can be resolved with an accuracy which corresponds to this ice thickness
Presentation	$A$ -scope and/or $Z$ -scope with unrectified video. Glacier surface elevation can be included in the $Z$ -scope picture

*The antenna*

A broad-band antenna is required to transmit a short pulse without distortion. Wu and King (1965) and Shen and King (1965) describe such an antenna. The internal impedance of a dipole antenna is given by

$$\mathcal{Z}^1(z) = \frac{\zeta\psi}{4\pi} \frac{2\alpha}{h-|z|}, \tag{1}$$

where  $z$  is the position along the antenna;  $\zeta = (\mu_0/\epsilon'\epsilon_0)^{1/2}$ , the intrinsic impedance of the media,  $\mu_0$  the magnetic permeability of free space,  $\epsilon_0$  the electric permittivity of free space,  $\epsilon'$  the real part of the relative permittivity of the low-loss medium surrounding the antenna;  $\psi = \psi(h, a, k)$  is a constant,  $2h$  the total length of the dipole antenna,  $2a$  the diameter of the dipole antenna,  $k = \omega/v$  is the wave number, and  $\alpha$  is a constant which determines the bandwidth of the antenna; the antenna can be made broad-band by selecting  $\alpha$  near to 1.

The constant  $\psi$  is found from

$$|\psi| = |[2 \sinh^{-1}(h/a) - C(2A, 2kh) - S(2A, 2kh)] + j/kh(1 - \exp(-j2kh))|, \tag{2}$$

where

$$\left. \begin{aligned} A &= ka, \\ C(a, x) &= \int_0^x \frac{1 - \cos \omega}{\omega} du, \quad \omega^2 = u^2 + a^2, \\ S(a, x) &= \int_0^x \frac{\sin \omega}{\omega} du, \quad \omega^2 = u^2 + a^2. \end{aligned} \right\} \tag{3}$$

If the antenna is placed on the surface of a glacier, the effective permittivity is  $\epsilon_{\text{eff}}' = (\epsilon_{\text{ice}}' \epsilon_{\text{air}}')^{1/2} = (3.2)^{1/2}$  (Ferrari and others, 1976). By selecting  $kh = \pi/2$ ,  $h = 15$  m, and  $a = 0.5$  mm one gets the angular resonance frequency  $\omega_0 = kv = 2\pi \times 3.8 \times 10^6$  rad/s;  $v$  is the wave velocity. Inserting these values into Equation (2) one obtains  $|\psi| = 18.8$  and from Equation (1) the internal impedance function is given by

$$\mathcal{Z}^1(z) = \frac{843\alpha}{h-|z|}. \tag{4}$$

The antenna is constructed by using lumped resistors to approximate the continuous impedance function. If one divides the antenna into  $n$  sections of equal length  $h/n$ , and a lumped resistor is inserted in each section, the value of the  $p$ th resistor can be found by integrating Equation (4) over the section

$$R_p = \int_{ph/n}^{(p+1)h/n} \mathcal{Z}^1(z) dz = 843\alpha \ln \left| \frac{n-p}{n-(p+1)} \right|. \tag{5}$$

If one re-numbers the resistors by writing  $R_q = R_{n-(p+1)}$  one gets

$$R_q = 843\alpha \ln \frac{q+1}{q}; \quad q = 0, 1, 2, \dots, n-1. \tag{6}$$

$R_q$  given by Equation (6) is the  $q$ th resistor counted from the end of the antenna towards the centre.  $R_0$  is chosen as

$$R_{0.1} = 843\alpha \ln \left| \frac{1.1}{0.1} \right| = 2.021\alpha \Omega.$$

In the present study one selected the constant  $\alpha = 0.1$  for the 2 to 5 MHz antenna. For

the 2 to 10 MHz antenna  $h = 7$  m and the constant  $\alpha = 1$ . The same type of antenna is used for the receiver and the transmitter.

The feed point impedance of the antenna is given by Wu and King (1965) for  $\alpha = 1$  as

$$Z_0 = \frac{\zeta\psi}{2\pi} (1 - j/kh). \quad (7)$$

The impedance is a resistance  $R_0$  in series with a capacitance  $C_0$

$$Z_0 = R_0 - j/\omega C_0, \quad (8)$$

where

$$R_0 = \frac{\zeta\psi}{2\pi},$$

and

$$C_0 = \frac{2\pi}{\psi} \epsilon_{\text{eff}}' \epsilon_0 h.$$

Inserting values for the present antennae in Equation (8) one gets

$$R_0 = 843 \Omega \quad \text{and} \quad C_0 = 79 \text{ pF},$$

for the antenna of resonance frequency 3.8 MHz and

$$R_0 = 843 \Omega \quad \text{and} \quad C_0 = 37 \text{ pF},$$

for the antenna of resonance frequency of 8.1 MHz.

The feed-point impedance of the antenna with  $\alpha = 0.1$  was estimated on the basis of values for  $\alpha = 1$  and  $\alpha = 0$  (ordinary dipole), and the matching network was adjusted in the field.

In order to make the transmitter load impedance resistive, a compensating network is connected across the antenna terminals. The network consists of an inductor  $L_0$  in series with a resistor  $R_0$ . When  $R_0^2 = L_0/C_0$  the input impedance becomes equal to  $R_0$  (see Fig. 4).

The antenna wire and the resistors were put inside 16 mm flexible plastic tubes which are easy to drag across the surface of the glacier.

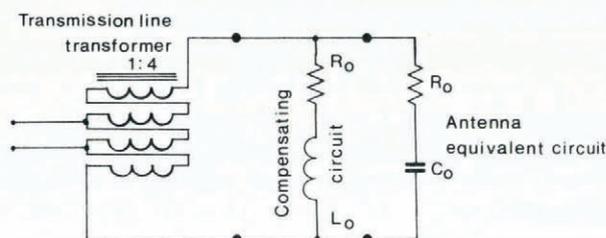
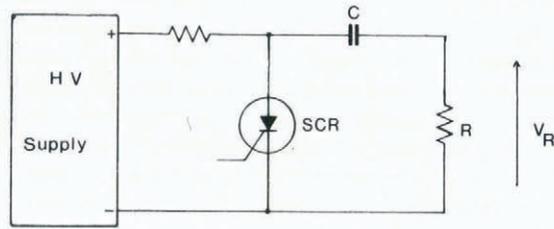


Fig. 4. Antenna matching circuit.

### The transmitter

The basic transmitter circuit is shown in Figure 5a. A capacitor  $C$  is charged to 1 200 V by the high-voltage supply HV. When the thyristor SCR is fired, the voltage across the resistor  $R$  first rises from zero to 700 V in 0.1  $\mu\text{s}$  and then decays exponentially. The output pulse is shown in Figure 5b. This circuit is capable of giving out pulses with a peak power around 10 kW at a repetition rate greater than 1 kHz.

A block diagram of the transmitter is shown in Figure 6. The transmitter is powered by a 12 V accumulator. The HV converter converts the 12 V to 1 200 V. The capacitor is charged to 1 200 V in 500  $\mu\text{s}$ . The thyristor is fired giving out a short pulse, 100  $\mu\text{s}$  after the



a

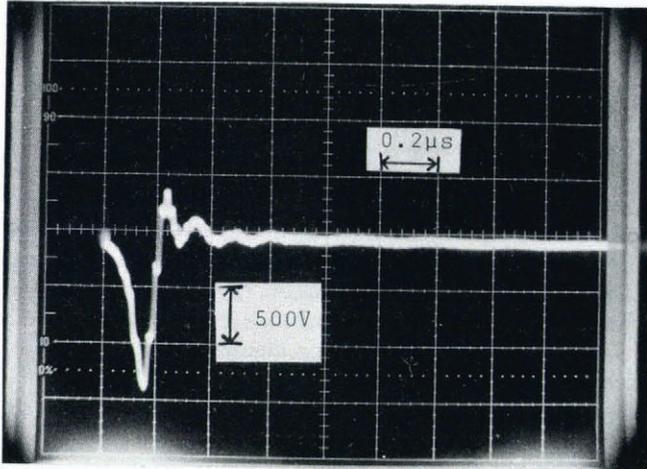


Fig. 5. (a) Basic transmitter circuit. (b) Voltage pulse across the antenna terminals for Mark I,  $\alpha = 0.1$ .

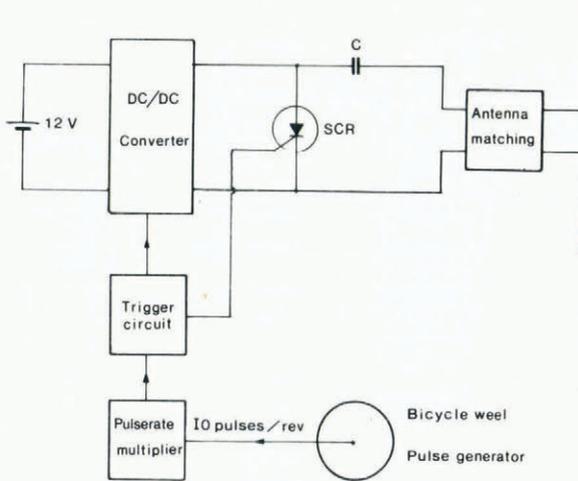


Fig. 6. Block diagram of transmitter.

thyristor is fired, the trigger circuit starts the HV converter and in  $500 \mu\text{s}$  the capacitor is charged to 1 200 V. Then the trigger circuit is ready to receive the next pulse from the pulse-rate multiplier PRM. The PRM receives an input from an a.c. generator which is placed inside a bicycle wheel that is attached to the transmitting sledge. The output pulse rate from the a.c. generator is directly proportional to the angular velocity of the wheel, thus making the pulse rate of the transmitter a measure of the speed of the transmitter sledge. The PRM converts the pulse rate from the a.c. generator to  $2^{14}$  pulses per 100 m advance of the sledge. The pulse rate of the transmitter is integrated in the receiver. The integration controls the deflection of the  $Y$ -axis in the  $Z$ -scope and marks a distance scale along the  $Y$ -axis.

The antenna impedance is matched to the transmitter by a broad-band transmission line transformer and an antenna compensation circuit.

The power consumption of the receiver is proportional to the repetition rate, being 12 W at 1 kHz.

### The receiver

The receiver block diagram is shown in Figure 7. The signal from the antenna-matching unit goes through a 2 to 5 MHz band-pass filter or, alternatively, it is connected directly to the video amplifier input. The video signal is amplified 20 dB in each stage of the video amplifier before it goes to a  $0.2 \mu\text{s}$  delay line. Leaving the delay line, the signal is further amplified 15 dB in the  $A$  and  $Z$  drivers. The overall amplification is, therefore, +75 dB and the band-width is 0.1 to 10 MHz. An attenuator can be inserted between the antenna matching unit and the amplifiers to reduce the overall gain when required. An output from the first stage in the amplifier goes to a triggering circuit which senses the start of the transmitter pulse. An output pulse from the triggering circuit unblanks the  $Z$  driver and thus enables the intensity of the oscilloscope beam to be controlled by the video signal. The trigger pulse also starts a sweep generator. The sweep generator gives out a rising voltage at the rate of  $0.835 \text{ V}/\mu\text{s}$  which controls the  $X$ -axis deflection of the oscilloscope. The result is a scale of 100 m ice depth per volt.

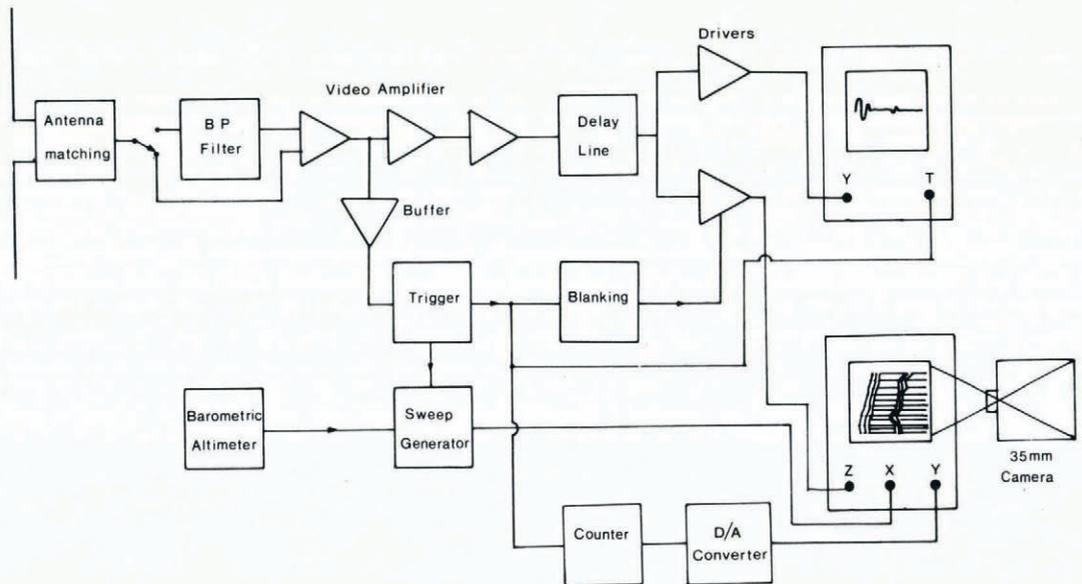


Fig. 7. Block diagram of receiver.

The starting position of the  $X$ -axis beam is controlled by the voltage from a barometric altimeter. The surface elevation of the glacier is, therefore, plotted on the screen and the bottom echo appears at the true height above sea-level. Figure 2 shows typical  $Z$ -scope pictures.

Pulses from the triggering circuit are divided by  $2N$ ,  $N$  ranging from 1 to 7, and counted in a 12 bit binary counter. The 12 bit output number is converted to analogue voltage in a digital-analogue converter. The  $Y$ -axis deflection is controlled by the analogue voltage and, depending on the value of  $N$ , the scale of the  $Y$ -axis can be varied from 25 m/V to 3 200 m/V.

In the  $A$ -scope mode, the trigger pulse  $T$  goes to the external triggering input on the oscilloscope and the  $A$  input to the  $Y$  input of the scope. A 35 mm reflex camera is mounted on the scope. In the  $Z$ -mode the camera is held open while the beam is scanning the screen. After scanning the whole screen, which takes several minutes, the film is advanced one frame and the  $Y$  counter is re-set, enabling the next frame to be scanned.

The receiver is powered from a 12 V accumulator and a d.c./d.c. converter supplies the various circuits with appropriate voltages. The total power consumption is 6 W for the receiver and 72 W for the Tektronix Model 465 oscilloscope.

#### EXPERIENCE

The device has shown good performance. Routine soundings are only limited by driving conditions and the visibility on the glacier. Sounding profiles of up to 50 km per day have been obtained on Vatnajökull. Navigation on the ice cap was done by LORAN-C and satellite navigation.

The maximum thickness measured so far is 800 m on Vatnajökull, but one presumes 1 000 m can easily be sounded. Crevasses show up on the records but only in exceptional cases has the bedrock reflection been wiped out.

Operating time must be chosen when the sky-wave propagation from short-wave radio stations is at a minimum, that is during daytime in the summer. Ground-wave propagation is usually not a problem because glaciers are mostly situated in remote areas. Interference from medium-wave broadcast stations has not caused problems for soundings at the glacier surface.

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