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RADIO AND ELECTRICAL MEASUREMENTS ON GLACIAL STREAMS

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Abstract. We discuss the suggestion that small under-water transmitters might be used to illuminate the interior of major englacial water channels with radio waves. Once launched, the radio waves would naturally tend to be guided along the channels until attenuated by absorption and by radiative loss. Receivers placed within the channels or at the glacier surface could be used to detect the signals. They would provide valuable information about the connectivity of the water system. The electrical conductivity of the water is of crucial importance. A surface stream on Storglaciären, in Sweden, was found, using a low-frequency technique, to have a conductivity of approximately 4×10^{-4} S m^{-1}. Although this is several hundred times higher than the conductivity of the surrounding glacier ice, the contrast is not sufficient to permit us simply to use electrical conductivity measurements to establish the connectivity of englacial water channels. However, the water conductivity is sufficiently small that, under favourable circumstances, radio signals should be detectable after travelling as much as a few hundred metres along an englacial water channel. In a preliminary field experiment, we demonstrated semi-quantitatively that radio waves do indeed propagate as expected, at least in surface streams. We conclude that under-water radio transmitters could be of real practical value in the study of the englacial water system, provided that sufficiently robust devices can be constructed. In a subglacial channel, however, we expect the radio range would be much smaller, the environment much harsher, and the technique of less practical value.

INTRODUCTION

The water associated with a temperate or sub-polar glacier plays an important role in determining the dynamic and thermal behaviour of the glacier but a role difficult to understand in detail, not least because the structure of glacial water channels, and the flow of water in them, are seldom well known. In this paper we discuss what might be learnt about the water channels by electrical and radio measurements carried out within them and we describe some relevant experiments recently carried out at Storglaciären in northern Sweden.

Our interest arose from radio echo-sounding. This can be used to obtain statistical information about the distribution of englacial targets (Walford and others, 1986). With considerable labour, we may use polarization-sensitive radio-echo aperture synthesis (paper in preparation by M.I. Kennett and M.E.R. Walford) to build up a specific, three-dimensional model of a local target distribution, limited in resolution by the radio wavelength and by the synthetic aperture. But radio-echo techniques cannot tell us how water bodies are interconnected, or what is the flow of water within the glacier. We have to rely on conventional hydrological techniques, particularly tracing, for such information. Such methods are valuable but have their limitations.

Radio-echo records from traverses often show the presence of characteristic, long, ringing echoes (Jacobel and Raymond, 1984; Walford and others, 1986) which may arise wherever radiation is trapped within sufficiently large water bodies. This observation suggests the possibility of deliberately launching radio waves from transmitters immersed within englacial water bodies; the radio waves would be expected to resonate or reverberate within closed water bodies and to propagate along continuous channels filled with water. This interesting possibility arises for glacial hydrology because the dielectric constant of water is much greater than that of ice at radio frequencies, and because the electrical conductivity of englacial water can be sufficiently small that rather low attenuation of radio waves occurs therein. Various potentially interesting experiments can be considered: the transmitters may be moored or they may be released, perhaps to make their way through the englacial waterways. The radio receivers may be emplaced in the water channels or at the glacier surface.

The transmitters must be small, battery-powered, approximately neutrally buoyant, and have tough, smooth, and flexible antennae. A suitable encapsulated construction would, we believe, make them sufficiently robust and waterproof to operate for a useful period of time, at least in some englacial water channels. However, transmitters should also be cheap, for we must anticipate that they would not normally be recoverable and would have their useful operational life-times limited by loss or by capture within some narrow portal, snag or whirlpool, if not by mechanical damage. Receivers placed within water channels must also be mechanically robust and must be provided with some system for relaying signals to the observer at the glacier surface. Depending on the circumstances, signals might be relayed by an electrical cable, an armoured optical fibre, an ultrasonic or a radio-relay link. The latter possibilities are electronically quite straightforward and offer the advantage of dispensing with what a referee referred to as the ever-fragile linking cable.

Experiments involving transmission between points within the water regime would be intended primarily to provide information about the channel connectivity. We have three proposals for experiments which employ receivers on the glacier surface: first, one might use the directional properties of receiving antennae in order to track the passage of the transmitter within the glacier as a function of time. Secondly, if the transmitter position was fixed, one could use an aperture-synthesis method to examine in detail the radiation from the channel system when it is internally illuminated with radio waves. Thirdly, it might be possible to transmit to the surface measurements of channel or water properties.

RADIO PROPAGATION IN WATER

The amplitude of a plane wave propagating in a weakly conducting medium decays exponentially with a characteristic decay length, $z_0 = 2c\epsilon_0(\epsilon')^{1/2}/\sigma$, where c is the speed of light *in vacuo*, ϵ_0 is the permittivity of free space, ϵ' is the relative dielectric permittivity of the water, and σ its low-frequency conductivity. In fairly pure water, $z_0 \approx 1/(20 \times \sigma)$ m at VHF. The low-frequency conductivity of surface water on Storglaciären was found to be approximately $4 \times 10^{-4}\,\mathrm{S\,m^{-1}}$ and $z_0 \approx 25$ m in the bulk liquid. In other words, the signal is absorbed at 0.35 dB/m in such water. The attenuation would be at least as great for waves propagating along an enclosed channel. This transmission distance is sufficient to be useful; it means that if we could build a system with, typically, a performance of order 100 dB, it would be possible under ideal conditions to detect signals with the transmitter and receiver separated by up to 300 m in a suitable water channel.

Because the dielectric constant of liquid water at radio frequencies, 81, is larger than that of ice, 3.2, a water channel can be regarded as a dielectric wave guide; indeed, it is a very effective one because the critical angle for total internal reflection in the water is only 11.46°. The theory of propagation in simple dielectric wave guides has been worked out in detail (see Ramo and Whinnery (1953) for a useful introduction, or Jones (1964) for a more detailed treatment). In a dielectric wave guide, TE and TM modes of propagation are possible for frequencies greater than a certain cut-off frequency, which is determined by mode, channel geometry, and the dielectric constants of both media. (A TE mode is a mode of propagation which is characterized by the electric-field components being wholly transverse to the wave-guide axis. In a TM mode it is the magnetic-field components which are transverse. Unlike the more familiar metal wave guide, no mode having wholly transverse electric- and magnetic-field components can propagate in a dielectric wave guide.) In a circularly symmetric, cylindrical, dielectric wave guide, the cut-off frequency for the lowest order TE or TM modes is approximately $13/a$ MHz, where a is the guide radius in metres. Hybrid modes can also exist for which neither the electric nor the magnetic field is wholly transverse. The cut-off frequency for the lowest hybrid mode is zero and this has the important implication that guided transmission can occur for any frequency. However, the electro-magnetic wave field is not entirely confined within the guide; an evanescent wave exists in the surrounding ice. The penetration length of this evanescent wave into the surrounding medium depends on the ratio of the dielectric constants and on the radio frequency. For water in ice, the ratio is high and so the penetration length is relatively small, except when the radio frequency is very close to the cut-off frequency for the mode in question. Then the penetration length tends rapidly to infinity and, for frequencies below cut-off, the dielectric acts as an antenna which radiates energy as the wave propagates along it.

In general, a naturally occurring water channel in a glacier may not be of a very regular shape. Fossil remnants of minor englacial streams, exposed in the ablation region at Storglaciären, commonly twist, turn, and vary in size particularly where they encounter moulins. This sort of behaviour is usually found where there is a high gradient and the stream has a rapid incision rate. A radio wave, launched along an englacial water channel of such convoluted geometry, would suffer partial reflection, mode change, and radiation loss wherever it encountered bends, scalloped walls or changes in radius sharp in comparison with the radio wavelength in water. Similar effects would also occur at places where the channel is too narrow for a given mode to propagate or where nearby inhomogeneities affect the evanescent wave outside the channel proper. On the other hand, some water channels, such as water-filled crevasses and larger rivers, are seen to be comparatively long, smooth, and regular in cross-section, and a relatively simple system of travelling radio waves might be found in these channels. The dielectric contrast between water and air is even greater than that between water and ice, and this would inhibit the loss of radiation from open channels unless the water surface was very rough. But the dielectric contrast between ice and the subglacial bed depends on the nature of the bed; it would be relatively small for a bed consisting of water-saturated sediments. In any case, Collins (1979) found that the conductivity of water beneath a glacier could easily be as much as 100 times that of englacially routed waters and this would heavily attenuate radio waves as they propagate along subglacial channels.

EXPERIMENTS

In order to test under fairly controlled conditions, whether propagation can occur in glacial water channels, experiments were carried out on a surface stream at Storglaciären during late August 1986. There was unusually little water present on the glacier for the time of the year, but a small surface stream was found of fairly regular cross-section (7–10 cm deep and 30–40 cm wide), sections of which could be cleared of its 10 cm cover of ice and snow to permit one to introduce radio antennae. So small a stream had not been anticipated so some rather simple equipment was improvised which operated at a frequency of approximately 85 MHz, corresponding to a wavelength in water of 0.40 m. The transmitter was an 85 MHz oscillator, amplitude-modulated at an audio-frequency of 1 kHz, which was coupled using coaxial cable to a thick dipole antenna, a half-wavelength (0.20 m) long in water. A receiving antenna was similarly coupled to a tunable receiver which consisted of a Radiospares transistorized dip meter. This provided an audible output signal but could not provide a quantitative measure of signal strength. With this simple apparatus, it was found that signals did indeed propagate along the water channel and could be detected up to 16 m from the transmitter. As an exercise, the apparatus was used to trace the connectivity of the stream along a 60 m length and to show that it was not connected directly to other nearby streams. Only within 1 m from the transmitter were signals detectable in air, using the dip meter connected to a dipole antenna a half-wavelength long in air. A fairly straight and uniform 3 m long section of the stream was cleared of its snow cover and it was shown that in this section the radiation consisted predominantly of travelling waves only and that the received signal was a maximum when both antennae were aligned *parallel* to the stream. This shows that the mode was in fact the lowest possible hybrid mode. It was also noticed that the frequency of optimum transmission for fixed antennae varied by a few per cent, depending on their precise local environment; this is attributable to variations in the resonant frequency and impedance of a radio antenna when it is confined in a narrow channel. In open water of low conductivity the impedance at resonance of a half-wave dipole is approximately 8 Ω.

ELECTRICAL RESISTANCE OF STREAMS

Low-frequency measurements of the conductance of surface and englacial streams were carried out using a four-terminal array in order to determine approximately the water conductivity and to assess whether such resistance measurements themselves might be of some diagnostic use to the glacial hydrographer. The choice of frequency is a compromise: at too high a frequency the conductance between electrodes in a stream would be dominated by the a.c. conduction in bulk ice or snow cover instead of the stream

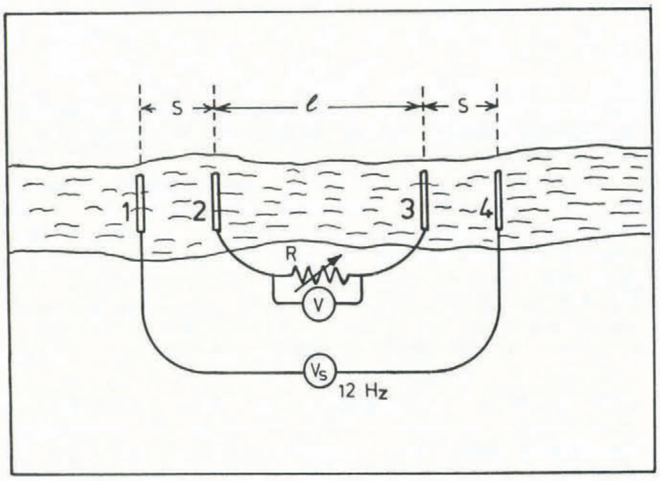

Fig. 1. Four-electrode array used to measure the resistance of a surface stream.

conductance in which we are interested, whereas at too low a frequency, electrode polarization can occur (Hobbs, 1974). After some preliminary field trials we operated at 12 Hz. The electrodes were copper strips laid across the stream (Fig. 1). An a.c. voltage source, V_S, of order 10 V r.m.s. was applied to the outer pair of electrodes (1 and 4) and the voltage $V(R)$, appearing at the inner pair (2 and 3) was measured with a high-input impedance meter as a function of R where R is the value of a load resistance placed in parallel with the voltmeter. The distance, s, between electrodes 1 and 2 was fixed at 1 m as was the distance between electrodes 3 and 4. The distance, l, between electrodes 2 and 3 was varied from 1 m to approximately 80 m. For each value of l we measured $V(R)$, as R was varied from 5 kΩ to infinity. The measurements were analysed in terms of the equivalent circuit shown in Figure 2, on the assumption that the system under study can be effectively represented by an ohmic resistor $S/2$ between electrodes 1 and 2, another between electrodes 3 and 4, and a resistor, L, between electrodes 2 and 3.

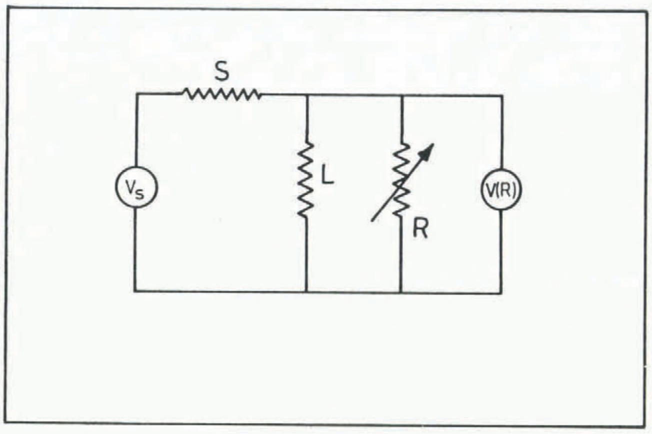

Fig. 2. The equivalent circuit of the arrangement shown in Figure 1. S represents the total series resistance of the voltage source, the resistance between electrodes 1 and 2 plus the resistance between electrodes 3 and 4. L represents the resistance between electrodes 3 and 4, which is the resistance of primary physical interest.

Theoretically

$$V_S/V(R) = (1 + S/L + S/R).$$

It was found for all the measurements that a graph of $1/V(R)$ against $1/R$ gave a very good straight line from which S and L could be calculated to better than 1%. The results shown in Figure 3 refer to measurements made in the same section of stream as were the radio-propagation experiments. L increases approximately linearly with l out to a few metres. For larger values of l, L is roughly constant with a value of about 400 kΩ. The values of S are more scattered and vary less systematically with l. This is as expected and is indeed one reason why a four-electrode measurement is preferred to a two-electrode measurement; S is sensitive to the local channel geometry and to the precise size and position of the electrodes. For small l, we have theoretically:

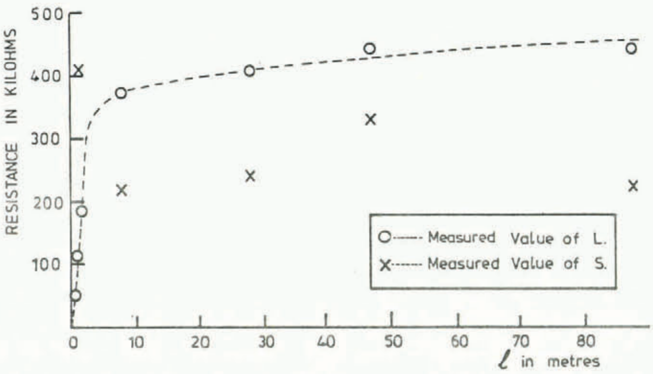

Fig. 3. L plotted as a function of l, the separation between electrodes 2 and 3, for a four-electrode experiment carried out in a small surface stream.

$$L = \int(1/\sigma_w A)\mathrm{d}l = l/\sigma_w A$$

where A is the channel cross-sectional area and σ_w is the conductivity of the stream water. Taking $A \approx 0.03\ \mathrm{m}^2$, we find that $\sigma_w \approx 4 \times 10^{-4}\ \mathrm{S\,m}^{-1}$. For $l >> 8$ m, we suppose that L is determined by bulk condition effects with an effective conductivity, σ_{ice}, of approximately $2 \times 10^{-7}\ \mathrm{S\,m}^{-1}$. These values should be regarded as correct to within a factor of 2 or 3, because of the uncertainty in the value of A. The contributions to the conductance of the stream and the bulk ice (if it is indeed an effect of bulk conduction rather than a surface effect related, say, to the expulsion of ions during freezing) are equal when $l = \sigma_w A/(2\pi s\sigma_{ice})$.

Some other related experiments will now be described briefly.

It was noticed that the voltage, $V(R)$, was non-zero even when the source V_S was switched off. The effect can be attributed to induced voltages either Man-made or natural in origin, possibly an effect of telluric currents. These induced voltages were approximately one-quarter of the amplitude of those observed with the source V_S switched on but fortunately were fairly constant with time. $1/V(R)$ varied linearly with $1/R$ and so they probably contributed no systematic error to our results.

Thermistor measurements at Storglaciären show that the ice temperature in summer is 0°C at the surface but falls below the melting point at depths of between ≈1 m and 30 m. During the period of our experiments there was also snow cover of approximately 10 cm thickness. We attempted to carry out a four-electrode resistivity survey of this layered system, at a site apparently clear of surface streams, with the electrodes pushed into the snow surface. It was found that a graph of $1/V(R)$ against $1/R$ was significantly non-linear, for reasons that are not clear and the results will therefore not be further treated here.

The stream which we studied was captured down-glacier by a moulin in which the water level was found (by electrical means) to be 17 m below the glacier surface. The effective resistance L was measured with electrodes 1 and 2 placed in the moulin water and electrodes 3 and 4 in the stream. It was interesting to see that the voltage readings, which had previously been stable to 0.1%, were in this case extremely noisy and difficult to read. This we attribute to fluctuations in the conductive path offered by the falling water, although there may also be e.m.f.s generated. L was 500 ± 50 kΩ, increasing slowly as the lower pair of electrodes descended through the water in the moulin.

There was a second moulin approximately 30 m from the first, both apparently occurring where streams were captured by a common crevasse. We lowered electrodes 1 and 2 into one and electrodes 3 and 4 into the other. In each the water level was found at a depth of 17 ± 1 m. The voltmeter readings were steady and the value of L was 647 ± 1 kΩ. If we suppose that this resistance was determined by conduction in a connecting channel of water 30 m long, of uniform cross-section and of conductivity $4 \times 10^{-4}\ \mathrm{S\,m}^{-1}$, we find that the cross-sectional area of this channel was approximately $0.1\ \mathrm{m}^2$. Of course, since the electrode pairs were 30 m apart, it may well be that the conductance was dominated by conduction in the bulk ice. A study of the conduction between the two surface streams feeding these two moulins showed that in this case conduction certainly appeared to be dominated by bulk conduction in the ice.

CONCLUSIONS

The radio techniques discussed in this paper could be very useful for exploring the englacial water channels in a temperate or sub-polar glacier, in cases where the conductivity of the water itself is not too great. A range of robust and thoroughly waterproof transmitters and receivers, operating at frequencies of tens and hundreds of MegaHertz need to be developed which can be introduced into the englacial system through bore holes or natural moulins or crevasses. The techniques are less likely to succeed in the case of subglacial water channels. Low-frequency resistivity measurements may also be of some use to the hydrographer but care will always be needed to test whether the apparent conductances are determined by the streams or by the surrounding ice. One may plot the apparent resistance as a function of separation as we did. Alternatively, it may be helpful to modify the conduction of the water by introducing salt into the channels.

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