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VERTICAL STRAIN MEASUREMENT IN CORE HOLES

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Abstract: The method of measuring vertical displacement in a bore hole developed by ROGERS and LA CHAPELLE (J. Glaciol., **13**, 315, 1974) has been adapted for core holes in polar ice sheets. The method uses metal bands injected into the hole as markers. The markers are located using a sensor consisting of an inductance coil in a tuned circuit that is detuned by mutual inductance as the coil approaches a conducting metal band. The principal change compared to the earlier instrumentation was an up scaling in size to accommodate a larger hole diameter and more robust construction of the components. Based on our experiences we suggest an improved band injection method.

1. Introduction

Vertical velocity affects the age and temperature fields in ice sheets. The associated strain rate distribution and the finite strain that develops are important for interpretation of the thickness of annual layers found in ice cores. Comparison of layer thicknesses with vertical velocity provides a means for testing for steady state flow dynamics and accumulation.

Vertical velocity is not routinely measured, primarily because it is not straight forward to do it. Normally vertical velocity is found through modeling assuming steady state balance with the current accumulation rate. Of course, this assumption is not true in general and one motivation for ice coring is to describe the evolutionary non-steady condition of environment and related changes in an ice sheet. Therefore it is valuable to measure vertical velocity.

We describe an adaptation of the method of ROGERS and LA CHAPELLE (1974) for measuring relative vertical velocity in polar ice sheet conditions. It was used successfully to measure vertical strain rate in a core hole of 234 m depth in the Dyer Plateau of the Antarctic Peninsula.

2. General Description of Instrumentation

The method is based on metal detection. Metal bands are injected into a core hole to serve as markers. The bands are located by a sensor that responds to nearby conducting material. The main requirements are techniques for emplacing the metal bands at desired locations in a vertical hole and for locating them with sufficient precision.

The bands are made from flexible metal (phosphor bronze) strip. The ends of the bands were prebent, so that adjacent layers lie snuggly against one another and the circumference of a hole (0.15 m diameter) when a band is coiled in the hole. To place a band into a bore hole the strip is coiled into a tube that is lowered to the desired location where it is thrust out of the tube by release of a spring loaded plunger triggered with a solenoid activated from the surface (Fig. 1a). Once expelled the strip expands to grip the circumference of the hole wall. It then forms a conducting ring in the hole. Based on trial injections into a tube (0.15 m diameter), the strength and throw of the ejection-spring assembly were adjusted to minimize the helicity of the band once it comes to rest.

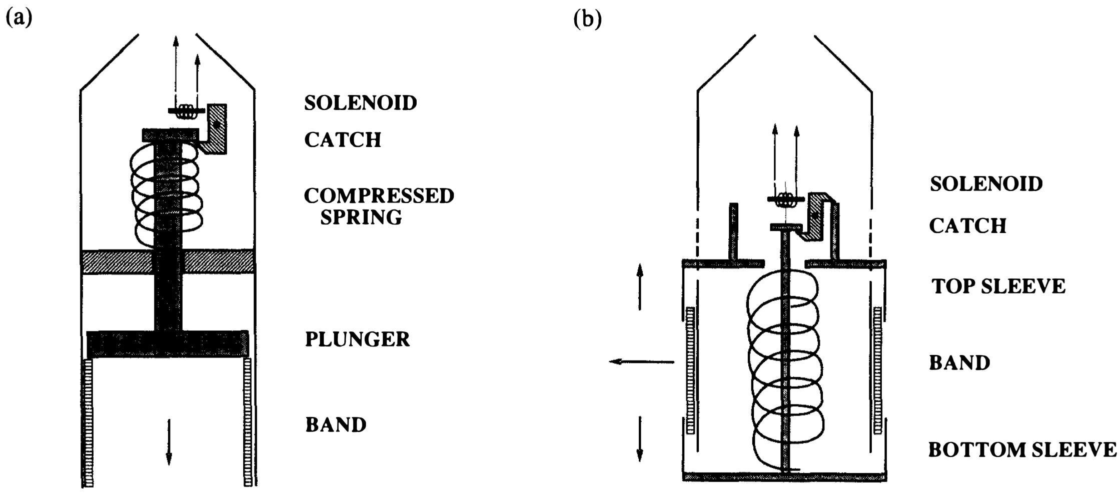

Fig. 1. Schematic of the band injector (a) and suggested alternative (b).

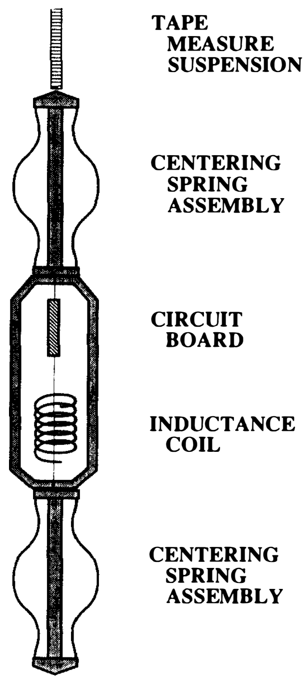

Fig. 2. Schematic of the sensor assembly.

The position of such a band is detected by an inductance coil in a tuned circuit powered by 4 AA 1.5 V batteries (Fig. 2). The circuit is detuned by the mutual inductance as the band is approached and entered, thus lowering the circuit output. The circuit is housed in a non-conducting pressure container with centering springs. The centering springs are set slightly smaller than the hole diameter, so the whole apparatus is freely suspended to maintain tension in a surveyors tape measure supporting it from the surface. This arrangement enables the measurement of the distance between pairs of bands (Fig. 3). The circuit output is transmitted to the surface through a twisted pair of wires that are taped to the tape measure at about 1 m intervals in a way that the wires support no tension and are fully supported by the tape measure. The circuit output can be read with a volt meter (2 V scale, mV accuracy, 60+ kHz band width).

The foundations of the method are described in detail by ROGERS and LA CHAPELLE (1974). This application differs from their method primarily in the dimensions of components and modifications of the circuitry as described in Table 1. The differences in thermal environment and scale lead to some differences in behavior.

Table 1. Equipment characteristics.

	Marker strip		
Length	Width	Thickness	Material
1 m	102 mm	0.404 mm	phosphor bronze spring sheet
	Band injector		
Diameter	Length	Weight	Material
127 mm	1.36 m	9.1 kg	aluminum, spring steel, nylon
	Sensor housing		
Diameter	Length	Weight	Material
102 mm	432 mm	4.1 kg	Nylon
	Sensor spring assembly		
Diameter	Length	Weight	Material
adj. to 153 mm	0.36 m		Nylon
	Sensor circuit		
Coil diameter	Power In (DC)	Signal (60 kHz)	Sensitivity
75 m	6 V (4 AA batteries)	1 V outside band 0.3 V inside band	0.1 mm/mv
	Sensor total		
Diameter	Length	Weight	
adj. to 153 mm	1.16 m	9.5 kg	

3. Procedure and Performance

In our application on the Dyer Plateau, fourteen metal bands were injected into the core hole at regular depth intervals between the surface and a depth of 225 m. These bands were then located relative to one another using a surveyors tripod mounted over the hole as

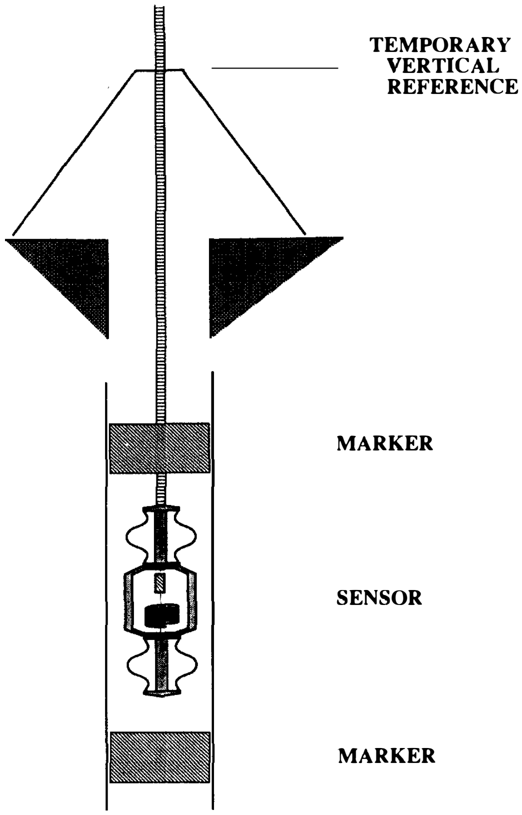

Fig. 3. Schematic of the measurement procedure.

a temporary vertical reference for reading the tape measure (Fig. 3).

Vertical velocity of the markers and the corresponding strain rate between markers was determined by locating the markers twice with an intervening interval of two years. In order to get absolute vertical velocity it is necessary that absolute coordinates of one point be determined in each down-hole survey. The best point would be the bottom, which in non melting conditions would have zero velocity. This was not done in this application, so only relative velocity and strain rate were determined directly.

An effective edge of the band was located by finding the position where the output was an average of the maximum distant from the band and a minimum in the band. Because of temperature sensitivity of the circuit and a temperature variation in the hole, it was necessary to measure the maximum, minimum and resulting average for each band over a short time interval. Practical sensitivity of the location measurement by this procedure was 1 mm and was limited by reading the tape measure. The accuracy could be increased by profiling the sensor output at closely spaced depth increments through the complete band width. This procedure would be tedious without automated data recording and was unnecessary for our measurements, which were limited in accuracy by the tape measure and the visual reading of it.

The bands were first located one day after injection in 1990 and then again about two years later in 1992. Table 2 summarizes relevant features of the results. On both occasions the same sensor and tape measure were used and the same procedure was followed. The top edges of bands were located in sequence as the sensor probe was lowered and then again as the probe was raised. In addition the bottom edges of the bands were located during the lowering phase and sometimes during the raising phase. The redundancy of the measurements give an indication of their reproducibility.

The agreement of location between the lowering and raising measurement was generally ± 2 mm or better (Table 2). In these cases an average of these two measurements on the upper edge was used to describe the location of the band.

Table 2. Summary of measurements.

Date	February 13, 1990				January 8, 1992			
M#	d_r (m)	Δ (mm)	w_r (mm)	δ (mm)	d_l (m)	Δ (mm)	w_l (mm)	δ (mm)
1	0.771*		107		3.220*			
2	13.622	+ 2	170		15.415	− 1	154	+ 2
3	26.116	+ 4	174	− 6	27.709	− 1	175	+ 1
4	38.620	0	163		40.065	+ 1	167	− 1
5	51.120	+ 1	171		52.447	− 2	171	
6	63.022	+ 2	164	+ 4	64.244	0	168	
7	76.100	+ 51	175	+ 99	77.232	0	170	
8	88.751	+ 71	263		89.795	− 3	265	+ 4
9	101.040	+ 1	163		102.052	− 1	168	
10	125.918	− 1	174		126.842	− 1	179	
11	150.968	− 1	171		151.813	− 1	178	
12	175.912	0	163		176.680	− 2	169	
13	200.910	+ 1	174		201.600	− 2	175	
14	225.912		163					

d: gives distance below reference to top of band; sub *r* indicates measurements on raising and sub *l* indicates measurements on lowering. Index location for the edge of a band refers to the sensor level where the sensor output is halfway between the output distant from the band and the minimum output when the sensor is positioned in the center of the band. The 1990 reference was approximately at the 1990 surface. The 1992 reference was approximately 0.5 m above the 1992 surface.

Δ: gives the difference between lowering and raising measurement.

w: gives the apparent width of the band; sub *r* indicates measurements on raising and sub *l* indicates measurements on lowering.

δ: gives the difference between apparent width measured during raising and lowering.

*: Measured directly to the physical top of band using a tape measure.

There were exceptions to this pattern on the initial measurement in 1990. (See bands 3, 7 and 8 in Table 2.) Bands 7 and 8 were located at a slightly bent portion of the hole identified by inclinometry, and their positions changed markedly between lowering and raising. These bands were apparently moved by the probe or the suspension during measurement at deeper locations. Possibly marker 3 was displaced as well, but the discrepancy between the lowering and raising measurement could have arisen from reading error on the tape measure, since the value was only slightly above values typical of the other measurements. These examples bring up the question of the stability of the markers at both obvious and more subtle levels, which is a crucial issue for the viability of the method.

The comparison of the location of the top and bottom edges of the bands gives an effective width of a band (typically about 170 mm) that is larger than the physical width of the metal strip forming the band (102 mm). This effect arises from the somewhat helical configuration of a band and the measurement procedure that locates an apparent edge that is somewhat outside the actual edge. The latter effect is expected from consideration of the mutual inductance. A non-unique helical pattern arising from the injection would contribute to scatter in the apparent widths. However, the apparent width of a single band appears to be reproducible between the lowering and raising measurement to the level expected from the reproducibility of the locations for the top and bottom edges. Hole closure over the interval between initial and final measurement would alter the configuration of a band. In order to get the sensor probe down the hole this closure can not be large, so the method is somewhat self limiting in this respect.

4. Discussion

A strategy to minimize the hazard of marker displacement during measurement is to use measurements on the raising for the initial measurement and for the lowering for the final measurement. A more robust solution to the problem would be to modify the band design or injection method so that bands are more securely fixed to the hole wall. Waiting longer than one day after injection before first measurement would also probably help to reduce susceptibility to displacement, which is suggested by the more stable behavior of the troublesome markers during the second time of measurement. Instead of injecting bands downward out of the end of a tube, it would be better to release bands sideways from the circumference of a tube (Fig. 1b), which would avoid velocity along the hole length and the resulting helical configuration when the band comes to rest. With this modification of method it could also be possible to inductively heat the band to melt it into and securely fix it to the core hole wall without any displacement of the injector body. This method of release would also accommodate roughness on the surface or edges of the bands that would act to prevent slippage. Fluid fill in the hole to suppress closure would help stabilize the markers over the extended interval between measurements and also guarantee access to the hole. However, fluid fill has other potential problems as discussed below.

Because the measurements in 1990 and 1992 were made with the same sensor freely suspended on the same tape measure in the same temperature and buoyancy environment, errors coming from changes in the distance scale between the two years should be negligible. If the hole is fluid filled and the fluid level changes between measurements, buoyancy effects will alter the tension distribution in the tape and accurate measurements are more difficult.

In our use of the method to about 200 m depth the system of taping signal wires to the tape measure was adequate, but inconvenient. It would be desirable to eliminate the signal wires as separate elements of the suspension. One way to do this would be to detect the circuit output locally and transmit it in digital form up the hole with an audio carrier, thus eliminating the need for wires. Alternatively, the signal wires could be built into the tape measure, for example as an accurate logging cable. These modifications would allow the sensor suspension to be operated with a winch and would be essential for use in deeper holes.

The practical accuracy of the method will probably be limited by the tape measure stability and method of reading. With the relatively crude approach taken in our application the accuracy we achieved for distance between adjacent markers was about 3 to

5 mm on baselines of 12.5 to 25 m corresponding to strain accuracy of about 0.4 10^{-3} or better. Average strain rate in the ice column on Dyer Plateau estimated from surface firn accumulation rate (~1.15 m a^{-1}) and full thickness (~365 m) was about 23 10^{-3} a^{-1}. Thus, with repeat measurement over a two year interval we had sufficient accuracy to resolve strain rate variation versus depth quite well. These methods should work well without modification for locations of low ice thickness and high accumulation rate such as on the Dyer Plateau. For locations with much greater depth and/or lower accumulation rate some modifications to get better accuracy would be needed.

Acknowledgments

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Reference

ROGERS, J. C. and La CHAPELLE, E. R. (1974): The measurement of vertical strain in glacier bore holes. J. Glaciol., **13**, 315-319.

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