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GLACIER SLIDING MEASURED BY A RADIO-ECHO TECHNIQUE

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ABSTRACT. An attempt to measure the surface velocity of a glacier by observing radio-echo fading patterns appears to have yielded instead a measure of the bottom sliding velocity.

RÉSUMÉ. *Glissement des glaciers mesuré par écho-radio.* Un essai pour mesurer la vitesse superficielle d'un glacier en observant les phénomènes de "fading" de l'écho-radio semble avoir donné à la place de ce qu'on attendait une mesure de la vitesse de glissement du glacier sur son lit.

ZUSAMMENFASSUNG. *Gletschergleiten, gemessen mit Radar-Echolotung.* Ein Versuch zur Messung der Oberflächengeschwindigkeit eines Gletschers durch die Beobachtung des Schwandes von Radar-Echos scheint stattdessen eine Messung der Gleitgeschwindigkeit am Untergrund geliefert zu haben.

WE HAVE measured the basal sliding of a glacier more than 1 000 m thick by observations from the surface. The sliding velocity was inferred from the difference between apparent surface velocities measured by two different techniques. The true surface velocity was determined by classical optical surveying using fixed marks on surrounding mountains. A radio-echo technique gave the surface velocity relative to a reflecting layer for radio waves near the ice–bedrock boundary. The difference between these velocities gave the motion of the reflecting layer relative to the glacier bedrock.

Nye and others (1972) suggested using radio-echo fading patterns to measure glacier surface velocities in areas remote from fixed rock outcrops. Walford (1972) demonstrated the method, which consists of using the bedrock beneath the ice cover as a fixed reference frame for measuring a surface displacement. However the presence of a wholly or partially reflecting horizon such as a layer of moraine, unresolved in range from the bedrock, means that either the radio-echo method measured the surface velocity with respect to this layer or that the fading patterns change with time (Nye and others, 1972).

We have repeated Walford's experiment on the same glacier (Fleming Glacier, Antarctic Peninsula) at a site close to his. Using a Scott Polar Research Institute Mark 4 radio-echo sounder working at 35 MHz, fading patterns were generated over an area approximately $11 \text{ m} \times 2.5 \text{ m}$ by moving the aerial in a series of parallel lines along a track. The track was calibrated to annotate the pattern with the distance moved from a reference stake fixed on the surface. Patterns were obtained over the period 13–20 January 1974. Great care was taken to ensure that experimental conditions were similar for each run.

The successive displacement of the fading patterns (Fig. 1) was observed by measuring the position of distinctive features with respect to the distance marks. A degree of judgement was necessary in determining the position of the features, so the readings were repeated a number of times and the mean taken. There was an apparently irregular across-track variation in the position of the features, so values obtained from parallel runs were averaged to give the along-track displacement only. As the track had been set up parallel with the direction of maximum surface slope (bearing 287° from true north) this procedure was unlikely to have a significant effect on the result. Table I shows the positions of three features over the period 13–20 January, together with the number of readings used to arrive at the value and the standard error in each case. Corresponding average daily velocities are shown in Table II. Since the standard error in each position is constant, the relative error in the velocity decreases with increasing time interval. Although there was a wealth of detail in the patterns, it was difficult to find features that were sharp enough to measure with reasonable accuracy and that were recognizable for the whole period.

The ice surface velocity determined by the radio-echo method was compared with the velocity calculated from an optical survey. Six reference objects on surrounding rock outcrops were intersected from each end of a 450 m base line on 31 December 1973. The position of the site was resected on 3 January and again on 26 January 1974. Two independent calculations by different methods gave the average surface velocity as 55±5 cm/d along 305° T.

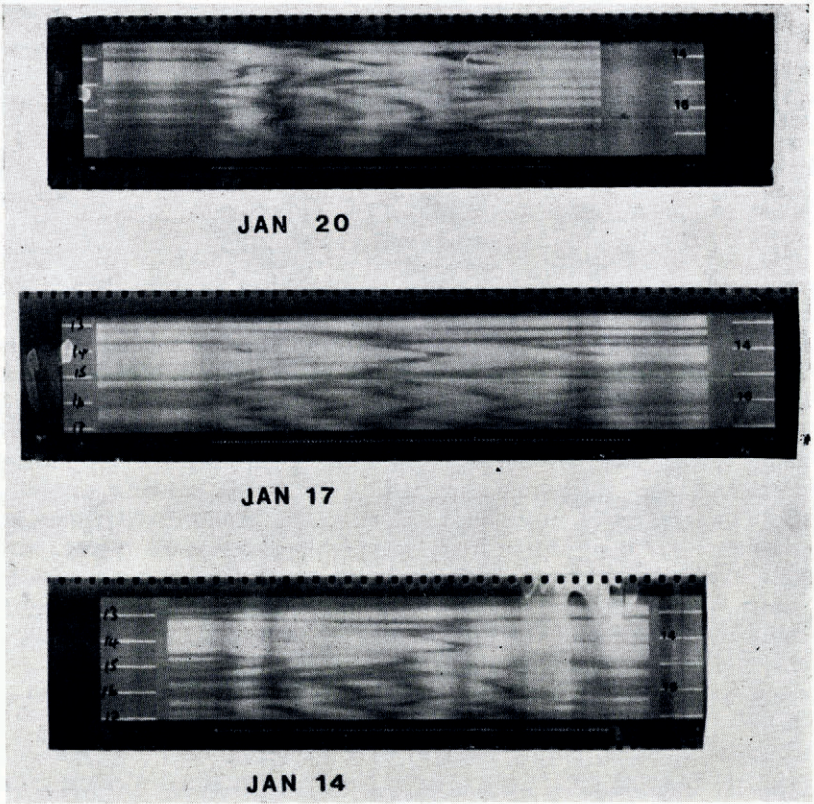

Fig. 1. Radio-echo fading patterns measured along the same line on the surface of the ice on three different dates in 1974.

TABLE I. MEASUREMENTS OF THE POSITIONS OF VARIOUS FEATURES OF THE FADING PATTERN

Feature	*Date January 1974*	*Horizontal position* cm	*Standard error* cm	*Number of readings*	*Time delay* μs
1	13	670		3	14
	14	660		1	
	15	595	2.4	43	
	17	515	3.2	42	
	20	404	3.7	42	
2	13	770		3	14.3
	14	740		1	
	15	704	3.4	29	
	17	615	3.3	52	
	20	533	3.2	26	
3	14	255	5.0	2	15.3
	15	195	7.6	11	
	17	112	3.7	18	

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(personal communication from J. L. W. Walton and R. Hayward). In spite of the experimental error in the radio-echo velocities there is a significant difference between the resulting mean velocity and the velocity given by the optical survey. We interpret this difference as being due to basal sliding or to rapid deformation of a basal reflecting layer.

TABLE II. APPARENT ICE SURFACE VELOCITY (cm/d)

Feature 1 From\To	14	15	17	20
13	10.4	40.9 ± 1.3	39.2 ± 0.8	39.9 ± 0.6
14		74.3 ± 2.7	48.3 ± 1.1	44.9 ± 0.7
15			37.7 ± 1.9	39.5 ± 0.9
17				41.0 ± 1.8
Feature 2 From\To	**14**	**15**	**17**	**20**
13	31.3	36.0 ± 1.9	39.2 ± 0.8	35.6 ± 0.5
14		41.1 ± 3.9	41.7 ± 1.1	36.3 ± 0.6
15			41.9 ± 2.2	35.4 ± 1.0
17				30.3 ± 1.7
Feature 3 From\To	**15**	**17**		
14	68.6 ± 10.4	47.7 ± 2.1		
15		39.0 ± 4.0		

Two conditions must be satisfied for this interpretation to be correct: the base of the ice must be at its pressure melting point, and there must be a layer reflecting at least as much radio energy as the bedrock. We assume that heat generated by friction and deformation in the basal layers is related to the surface velocity (Paterson, 1969). Transforming this to an additional basal heat flux and using steady-state models (Budd, 1969) indicates that the Fleming Glacier is at its melting point at the site of the experiment. If the ice is thickening as it flows down-stream through the site, conditions are suitable for the formation of a basal temperate layer (Lliboutry, 1966). A basal reflecting layer could then consist either of moraine or of a layer of ice at the melting point with slight variations in water content.

While the radio-echo method of measuring ice surface velocities may give false values in areas where basal sliding occurs, where true velocity can be checked by other means the technique appears valuable for learning about conditions near the base of the ice. Doppler satellite receivers now offer a reliable but expensive means of determining surface velocities on ice sheets.

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DISCUSSION

D. J. Drewry: You suggest that your fading patterns are generated by targets near to the base of the ice and moving at the inferred sliding velocity. Might not a mobile layer of till or moraine, deforming at a slower rate, provide the reflecting centres? The fading patterns would, in this case, be unstable with time.

C. S. M. Doake: We would expect a certain amount of shear at the base of the ice and the reflecting layer could well be in this region. The effect of shear on the reflecting layer could give a churning motion of the scattering centres, producing a change with time of the fading pattern.

J. F. Nye: To observe whether the fading pattern is stable with time or not it would be desirable to make the second traverse nearly precisely over the same line on the bed as the first. This could be achieved by making equally spaced, parallel runs as you have done, but with the difference that the spacing of the second set is made slightly different from that of the first. Then, like lines on a vernier, two of the runs will be very close together.

Doake: This is a good idea, but I wonder how much would be gained over using our spacing of 10 cm between parallel lines. Patterns taken on adjacent lines show very little difference, and a powerful pattern-comparison technique would be required to distinguish between any two patterns closer together than 10 cm.

S. Evans: In the discussion of the positional accuracy of fading patterns I would like to call attention to the finite size of the antenna absorption cross-section. However small the antenna is made the cross-section will not be less than *c.* $0.1\,\lambda^2$. Positional measurements can be more precise than this only when the signal-to-noise ratio is large.

G. de Q. Robin: Data are available for spatial mapping of the fading pattern over say $8\text{ m}\times 2\text{ m}$ of a spacing of 20 cm. Will this not, (1) give a better reference framework than linear measurements and (2) provide a better framework for seeing whether the fading pattern varies with time?

Doake: The data could certainly be used to construct an areal reference framework. This in effect is interpolating between the patterns taken on parallel lines, and could therefore be used for measuring a displacement. In answer to your second point the areal reference framework would essentially be in four dimensions (X, Y, time delay, and intensity or echo strength) but could readily be used in three (X, Y, and intensity) for a given time delay. It would be interesting to produce these 3-D surfaces to see changes in fading patterns with time.

J. W. Glen: Could one not measure fading patterns along orthogonal sets of lines so as to avoid having to make a map as suggested by Dr Robin? Such lines, executed on a vernier principle, should give two tracks, at right angles, over essentially the same positions.

Doake: The use of orthogonal lines, repeated on a vernier principle, should match the measurement of the velocity vector more easily. In the present work, using parallel lines, we found the measurement of the cross-track velocity component difficult in practice.

M. E. R. Walford: We plan to survey a rectangular network of points and repeat this survey at a later date with a parallel grid of slightly different spacing. We can thus measure velocity in both X and Y directions and make use of Professor Nye's vernier principle. The measurements of Dr Doake and Dr Swithinbank and my own were made at different times. I note, however, that the "odd-man out" of the group of our four measurements is the conventional optical survey which accompanied Dr Doake's survey.

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DOAKE: The ratio of the optical survey velocity to the radio-echo velocity is 1.21 for the 1972 results and 1.25 for the 1974 results. This close agreement shows that the two seasons' results are comparable. The systematic difference may be due to the two sites not being at the same place but separated by probably 1–2 km.

O. ORHEIM: Does the fading pattern alter with change in the vertical position of the radio-echo sounder? If this were the case it might explain why you were unable to obtain exactly the same pattern on Fleming Glacier since in following the ice surface a change in thickness could take place over the period of measurement.

DOAKE: We watched the bottom echo whilst lifting the aerial vertically 2 m off the ice surface, and saw no appreciable change. It appears that the fading pattern is at least an order of magnitude more stable for vertical movements than horizontal movements. As the surface slope is about 0.5° at the Fleming Glacier site there was negligible vertical movement over the period of the experiment.