The Bedrock Topography Deduced from Multiple Radar Echoes Observed in the Mizuho Plateau, East Antarctica

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東南極みずほ高原で観測されたレーダー多重反射から求めた岩盤形態について

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要旨： 日本南極観測隊はみずほ高原を中心に，電波氷厚計を用いて，氷厚の測定を行った．観測される電波エコーは，多重反射を示している．NARUSE と YOKOYAMA は，エコー時間の最も長いエコーを岩盤からの反射と仮定して，氷厚を計算した．

しかし，岩盤の細い凸凹に起因するといわれている "spatial fading 効果" によって，岩盤からのエコーの欠落が起こることが知られている．また，岩盤表面が大きなスケールで起伏している場合には，岩盤からのエコーよりもエコー時間の長いエコー，あるいは短いエコーが観測されることも知られている．したがって，上記の仮定はかならずしも正しくない．

この論文では，上記の効果を考慮して多重反射エコーを総合的に解析し，より妥当な氷厚および岩盤形態を導き出した．みずほ高原の相当部分，少なくともルートA以北の大部分では，底面すべりが起こっており，底の岩盤上に水が存在することを考えて，得られた岩盤地形のある部分 (図 2 の V–W 谷) には，氷下湖の存在する可能性があることを示した．

***Abstract*:** Taking into account the effect of spatial fading and erronous echoes caused by large scale undulations of bedrock surface, the radar echo data by the 14th Japanese Antarctic Research Expedition were reanalysed to obtain the ice thickness and bedrock topography in the Mizuho Plateau area. The bedrock topographies along three Routes A, C and S are drawn by solid lines in Figs. 3, 4 and 5 respectively. Even though slopes on the bedrock were smoothened, there remain some steep ones which satisfy the condition of the existence of a sub-ice water lake. Since it was expected from the data of surface velocity measurements along Route A that the basal sliding was taking placing with the ice sheet north of Route A in the Mizuho Plateau, it is probable that there exist a sub-ice water lake along the valley indicated by a dotted line V–W in Fig. 2.

1. Introduction

Since the bedrock topography is very important for understanding the flow and surface morphology of ice sheets, various kinds of techniques for the measurement of

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the thickness of ice sheets have been developed. Among the techniques, a pulsed radar method is the most useful because radar instruments are easily installed in airplanes or over-snow vehicles.

For the measurements of ice thickness in the Mizuho Plateau, the Japanese Antarctic Research Expedition (JARE) used a radar echo sounder designed by Scott Polar Research Institute. In general, the echoes observed on the oscilloscope of the sounder were not single but multiple, as shown in Fig. 1. In calculating the ice thickness in this area, NARUSE and YOKOYAMA (1975) simply assumed that a echo with the longest time delay was reflected from the bedrock surface just below the observation point. Based on the calculated ice thickness, OMOTO (1976) and SHIMIZU *et al.* (1978) represented the profiles of the bedrock surface. However, examinations of many echo pattern examples obtained in other area of Antarctica and in Greenland revealed that their assumption was not always correct. For example, the phenomenon called "spatial fading" due to the roughness of the bedrock surface causes weak or even no echo from the bedrock surface (OSWALD, 1975). Moreover, as shown in Figs. 4 and 6 of GUDMANDSEN's paper (1970), in the case of a wavy bedrock surface we can sometimes observe echoes with the longer time delay than that from the bedrock just below the observation point. Therefore, in the case of point-to-point measurement from the ice surface adopted by JARE on its traverse trip on the ice sheet in the Mizuho Plateau, it is necessary to re-examine the echo pattern for constructing reasonably correct profiles of the bedrock.

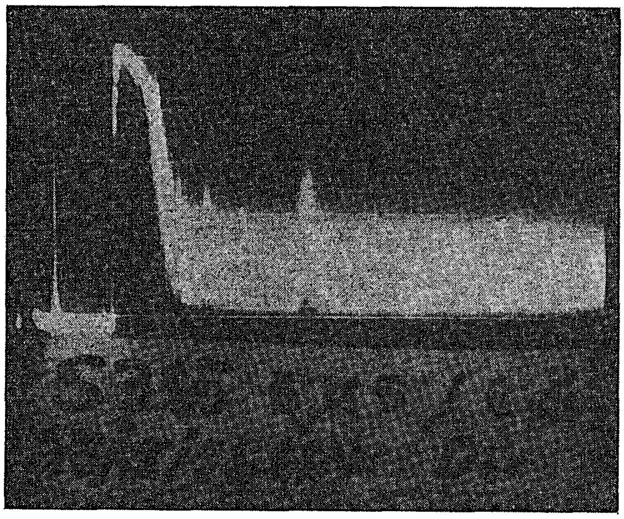

Fig. 1. Typical example of radar multiple echoes.

NARUSE and YOKOYAMA (1975) reported results of the time delay of the multiple echoes observed along the traverse routes shown in Fig. 2. Along Route A a triangulation survey and its resurvey were carried out in November–December 1969 and in

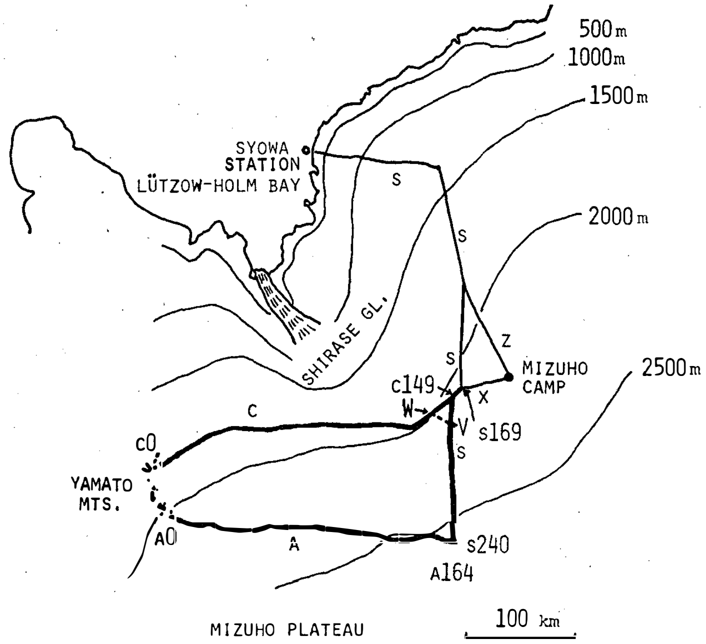

Fig. 2. Map of traverse routes radar echo sounding.

December 1973–January 1974, respectively, for the estimate of the flow of the ice sheet. Analyzing the results of the survey, NARUSE (1978) obtained horizontal and vertical flow velocities of the ice sheet on its surface, the surface strain rates and the time rate of the variation of the ice thickness along the route. However, along the other routes no measurement of the flow velocity and the strain rate was made. The flow lines on Routes A and C are now known to be almost perpendicular to the routes, while Route S (from No. 169 to No. 240) lay almost along the flow line. Since no echo sounding was tried along the flow line direction on Route A, the records of the radar echo obtained along Route S provide informations on the bedrock topography along the flow line in this area.

In this paper, the radar echoes observed along Routes A, C and S (a segment between No. 169 and No. 240 from the whole Route S on Fig. 2 will be cited as Route S hereafter) were re-examined to obtain more reasonable and accurate depth of ice along those routes. The obtained results were analyzed with the results the triangulation survey and a possibility of existence of the sub-ice water lake in northern part of the Mizuho Plateau is proposed.

2. Multiple Echoes along Routes A, C and S and the Determination of Bedrock Surface Topography

From the field data reported by NARUSE and YOKOYAMA (1975), the profiles of the depth of multiple echoes along Routes A, C and S are drawn in Figs. 3, 4 and 5 respectively. The surface elevation along each route (SHIMIZU, 1977) was also drawn in each figure. In order to estimate the depth of the echoes plotted on these figures, 171m/μs of the radar wave velocity in ice was multiplied to every value of multiple echo times tabulated in NARUSE and YOKOYAMA's report. In Figs. 3 and 5 the depth of multiple echoes are clearly divided into two groups; one is at the intermediate depth and another

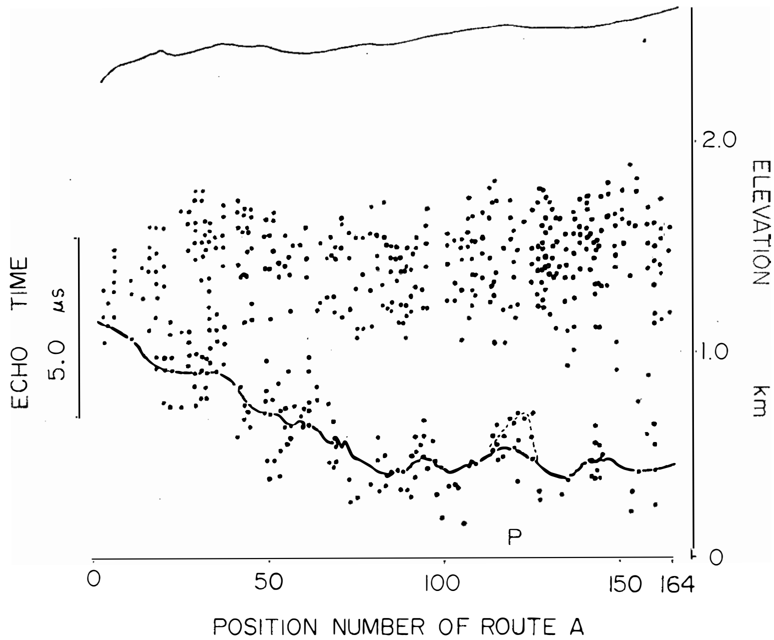

Fig. 3. Profiles of multiple echoes (solid circles) and topographies of the ice sheet surface (thin line) and bedrock surface (thick line) along Route A.

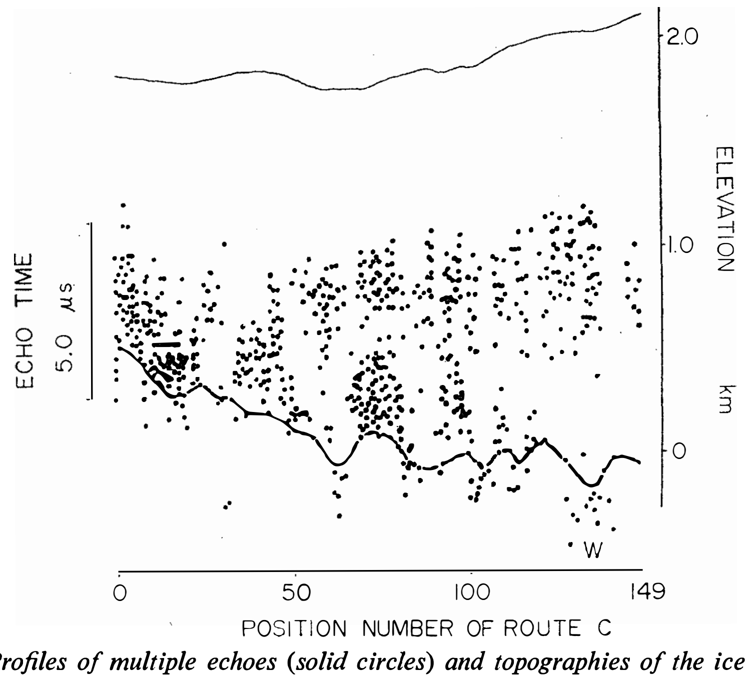

Fig. 4. Profiles of multiple echoes (solid circles) and topographies of the ice sheet surface (thin line) and bedrock surface (thick line) along Route C.

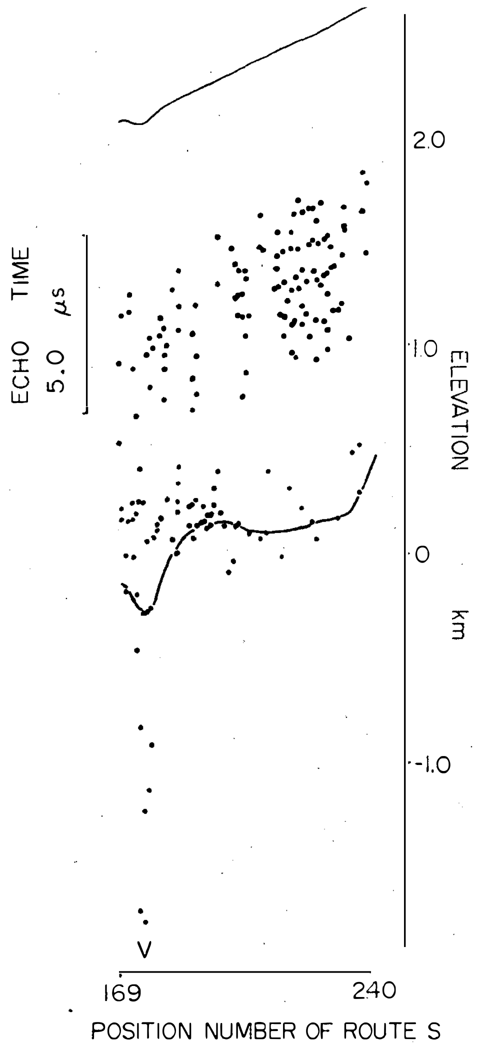

Fig. 5. Profiles of multiple echoes (solid circles) and topographies of the ice sheet surface (thin line) and bedrock surface (thick line) along Route S.

is near the bedrock surface. The group scattered at the intermediate depth may correspond to layers of echo pattern frequently observed in the photographic records of continuous measurement by the air-borne radar (for example, ROBIN *et al.*, 1969). That is to say, the scattered dots at the intermediate depth in Figs. 3 and 5 are to be caused by the same reason as the layer pattern of the echoes. In Fig. 4, the group at the intermediate depth seems to overlap on that near the bedrock surface. The difference between the patterns of multiple echoes appeared in Figs. 3 and 4 may be caused by the difference in the structure of ice due to the flow and also by the temperature along Routes A and C.

In order to determine the depth of the bedrock, we examined only the group of echoes from near the bedrock surface. Even if the bedrock surface under the ice sheet in the Mizuho Plateau is approximately flat, the roughness of the bedrock surface with a horizontal scale of 20 m or less and a vertical scale comparable to the radar wave length

($\lambda \fallingdotseq 5$ m, 35 MHz radar) may exist and it may cause the phenomenon called "spatial fading" when the radar wave reflects from such a small undulation of the order of wave length. The spatial fading is primarily caused by interference of coherent waves and it appears as repetitions of weak (or no) echoes and strong echoes in a continuous record of the air-borne radar echo sounding (OSWALD, 1975). Although OMOTO (1976) did not point out, the spatial fading is revealed in Figs. 8 and 9 of his paper which show the continuous record of the radar echo sounding between S 18 and S 19 and between S 36 and S 37 in the coastal area.

Precise examinations of the records of radar echoes obtained by GUDMANDSEN (1970) reveal that echoes of longer or shorter time delay than to be expected from the real bedrock surface are often observed for its undulations of large scale)≫ radar wave length). The nominal depth of reflection is deeper below the bedrock for concave surface and is shallower above the bedrock for convex surface. Amount of such deviation in the delay time reaches to several microseconds and consequently it gives rise to error of several handreds meters in the measurement of depth of ice. Figs. 8 and 9 of OMOTO's paper reveal that there are two or three layers of the echoes near the bedrock of which the elevation difference exceeds 200 m. It is most likely that these multiple layers near the bedrock surface are caused by the undulations stated above.

Considering the spatial fading phenomenon and the effect of large scale undulations of the bedrock surface, the bedrock topography along Routes A, C and S were determined as drawn by the solid lines on Figs. 3, 4 and 5 respectively. The lines were drawn among the points of echo depth near the bottom, not connecting the deepest points or those of longest time delay but smoothening the trends of distribution of points. Fig. 6 is one example of the comparison of the ice depth profile determined by the present method (solid line) and that by connecting the deepest points (dashed line) along Route S. It is not likely that there are approximately 10 ridges and troughs of nearly 1,000 m altitude difference in 100 km distance along the direction near to the flow line as indicated by the dashed line. Therefore, the solid line should be more realistic profile of the bedrock topography.

There still may remain a doubt that why I did not draw the line as such that indicated by a dashed line around point P in Fig. 3. If we conscientiously follow the principle of drawing stated above, the dashed line seems to be more reasonable. GUDMANDSEN (1970) found that the layer structure at the intermediate depth of the radar echoes was broken up over such a steep hump of the bedrock. However, we did not find any sign of faults or disappearance of echoes from the intermediate depth on both sides of point P. Therefore, the profile of the bedrock around point P was smoothened out as the solid line. In Fig. 5, there is a valley V near the northern end of Route S. The depth of the valley is 3,870 m from the ice surface due to the longest time delay but it is about

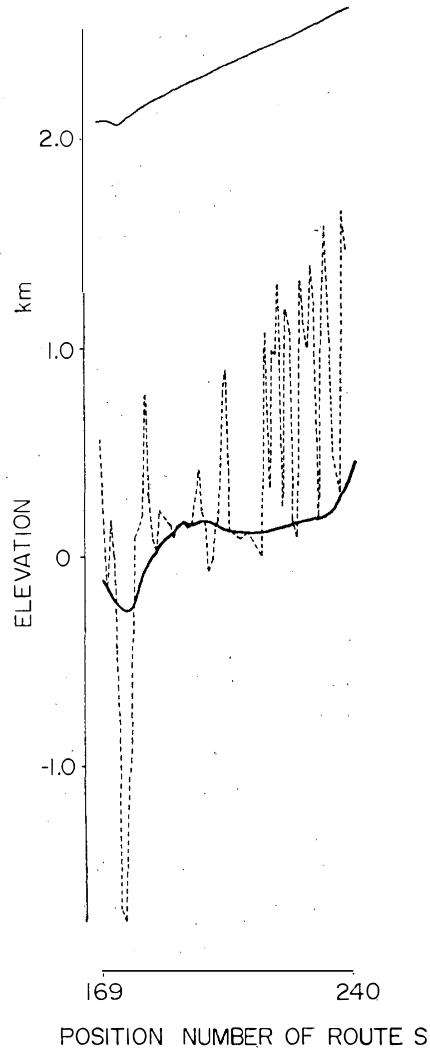

Fig. 6. Topography of the bedrock surface along Route S. The solid line indicates the result of the present work and the dashed line indicates the result obtained from the ice thickness computed by NARUSE *and* YOKOYAMA *(1975).*

2,260 m on the solid line determined as above. Since this valley is believed to be connected to the valley W on Fig. 4 from the contours of bedrock (see dotted line on Fig. 2), the depth of both should coincide approximately, *i. e.* about 2,300 m. Therefore, several deeper echoes observed should be some erronous ones caused by concave topography of the bedrock around point V.

3. Discussion

OMOTO (1976) reported that the profile of the bedrock obtained by connecting the deepest echo depth along Routes A and S was very different from the result of the gravity measurement. In Fig. 7 the present result of the bedrock depth profile along Route A drawn by the solid line in Fig. 3 is compared with results obtained by the gravity measurement (YOSHIDA and YOSHIMURA, 1972). Coincidence of the large scale undulations along the route is generally good among these curves. Similarly, the

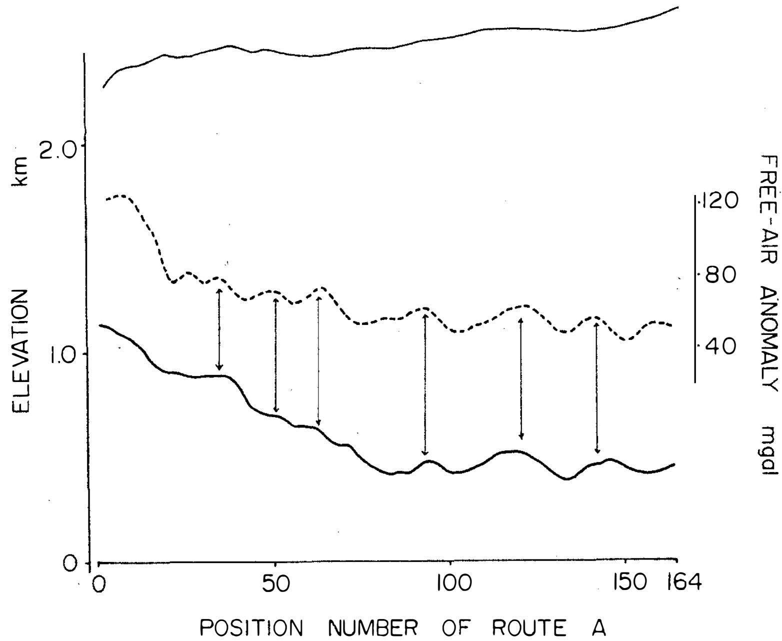

Fig. 7. Comparison of the bedrock profiles along Route A obtained by the present method (solid line) and the gravity measurement by YOSHIDA *and* YOSHIMURA *(1972) (dashed line). Arrows indicate corresponding concave undulations of the both profiles.*

present result coincides fairly well with the gravity measurement along Routes C and S.

Although steep slopes obtained by connecting the deepest echoes (like dashed line in Fig. 6) were very much smoothed out in the present result, there still remain some steel slopes at point V on Route S and point W on Route C. Those slopes satisfy the morphological criterion for the existence of a sub-ice water lake under the ice sheet; $\alpha_b \simeq 10\ \alpha_s$ where α_b is the slope of the bedrock and α_s is the surface slope (OSWALD and ROBIN, 1973). It was anticipated from the veloctiy measurement along Route A that there occurs the bottom sliding of the ice sheet in the northern area of the Mizuho Plateau due to the existence of water film in the bottom of ice sheet (MAE, 1977). Therefore, it is probable that there exists a sub-ice water lakf along the valley connecting points V and W (indicated by dotted line in Fig. 2) and it will be an interesting subject to detect it by a precise radar echo sounding in this area.

OSWALD (1975) pointed out that the spatial fading length appearing on the continuous records of radar echo extends more than 200 m when water film exists at the bottom. Although it is a remarkable sign compared with approximately 5 m of the fading length on the ordinary dry (frozen) bedrock, such difference was not detected from the JARE observation data which was taken intermittently at about 2 km intervals. It is very much desirable therefore to carry out a continuous radar echo sounding from an air-plane in the next survey of depth profile on the Mizuho Plateau area. Such the radar sounding will provide not only the depth profile but also the informations of existence or non-existence of water at the bottom of the ice sheet. The air-borne radar echo sounders for this purpose are now in preparation at the National Institute of Polar Research.

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