Radio echo-sounding of King George Island ice cap, South Shetland Islands, Antarctica


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Results of ground-based radio echo-sounding collected along the main ice divide of King George Island ice cap in December 1995 by means of 40 MHz monopulse radar are presented and discussed.

Introduction

Field work was performed in November — December 1995 by a seasonal detachment of the 41 Russian Antarctic Expedition on Bellingshausen Station and by the International Glaciological Expedition organized by the Federal University of Rio Grande do Sul, Brazil and were carried out within the frames of SCAR supported International Program “Glaciology of South Shetland Islands” (GLASS) aimed at the investigation of contemporary state and evolution of subpolar ice masses of the Antarctic region and at estimation of their response to short-term environmental changes.

King-George Island, the largest (1313 km2) of the South Shetland Islands (Fig. 1), is suitable for these investigations considering its location on the way of the main moisture-laden cyclones feeding the glaciers in the western section of the Antarctica. This ice cap consists of a few ice domes up to 700 m in elevation that are drained by a series of relatively fast-moved tide-water outlet glaciers (Fig. 2). These glaciers are the main source of ice discharge due to summer melting and ice calving which is filling up by intensive winter and summer solid and liquid precipitations. Therefore, a more detailed study of these dynamically active parts of the ice cap can be considered a key for understanding its present state, regime and dynamics and its response to short-term climate variations.

To study the evolution of this ice cap it is important to know the temporal changes in area and volume, mass balance, equilibrium line altitude (ELA), ice formation zones and the structure of snow—firn sequences. For forecasting of these changes, by means of numerical modelling, it is needed to know the distribution of contemporary mass balance on the glacier surface, its long-term variations, thermal regime, glacier surface elevation, ice thickness and subglacial relief.

Previous data on these characteristics of ice masses in South Shetland Islands are limited by 10 — 40-years period — since the large-scale aerophotography survey in 1956/57 [Simões and Bremer, 1995] and the start of mass balance measurements in King George, Livingston, Deception and Nelson Islands in 1968 — 1984 [Goveroukh and Simonov, 1973; Zamoruyey, 1972; Orheim and Goveroukh, 1982, Ren and others, 1995] up till the analysis of satellite images collected in King George and Livingston Islands in 1979 — 1995 [Calvet and others, 1992, Simões and Bremer, 1995]. The studies of ice cores from bore-holes of 10 — 70 m deep [Studio..., 1993: Ren and others, 1995] and ground-based and airborne radio-echo sounding measurements of ice thickness were also carried out in King George (Fig. 2) and Nelson Islands [Ren and others, 1995]. The ground-based measurements in King George Island were conducted by 15 Soviet Antarctic Expedition in 1970 [Goveroukh and others, 1974], by a Chinese-Uruguayan Expedition in 1992 [see Simões and Bremer, 1995] and by 40 Russian Antarctic Expedition in January 1995 [Glazovskiy and Moskalevsky, unpublished] in 18 km long section in western part of the ice cap including Collins ice dome located in 3 — 6 km from Russian and Uruguayan research stations Bellingshausen and Artigas. In

![Map of South Shetland Islands](image)

Fig. 1. Index map of South Shetland Islands
Рис. 1. Карта Южных Шетландских островов
Рис. 2. Радиолокационное зондирование ледникового купола на острове Кинг-Дордж. 1 — свободная ото льда суша; 2 — края ледника; 3 — основные ледниковые купола; 4 — положение ледораздела на куполе В; 5 — выходные ледники; 6 — точки наземных радиолокационных измерений в декабре 1995 г. и их номера; 7 — профиль наземного радиозондирования 15-й Советской антарктической экспедиции в 1970 г. (Говоруха и др., 1974); 8 — линия полета Британской антарктической экспедиции в 1975 г.; 9 — буровой лагерь в декабре 1995 г.; LG — выездной ледник Ленж.

Nelson Island they were carried out by Chinese Expedition in 1985 in northern part of ice dome [Ren and others, 1995]. A RES survey flight (flight 38) was made by British Antarctic Survey in 1975 over the entire King George Island ice cap [see Simões and Bremer, 1995].

The warm firn zone prevails in the accumulation areas of South Shetland Islands glaciers due to combination of glacioclimatic factors such as low EL position (140 — 370 m in altitude) and ice temperatures close to melting point [Orheim and Gоворуха, 1982; Ren and others, 1995]. A close link between average mass balance and ELA on G1 Glacier (Deception Island) and Collins ice dome (King George Island) was also marked and noticeable changes after volcano ash falls caused by volcano eruption on Deception Island in 1970 were revealed [Orheim and Gоворуха, 1982].

On King George Island ice cap two main facies were identified in summer (29 February 1988) and winter (24 June 1992) SPOT and ERS-1 SAR satellite images [Simões and Bremer, 1995]. One of these facies is characterized by high and low surface reflectance and backscattering, respectively. In summer SPOT images these facies are related to the percolation and wet snow zones (higher surface reflectance) and to ablation and superimposed ice zones (lower surface reflectance). The boundary between them was interpreted as the transient snow line. In 1988 its altitude was about 300 — 350 m a.s.l. and in March 1995, according to field observations, it was 450 m a.s.l. In winter ERS-1 SAR images the lower backscattering coincides with a bare ice zone covered by a thin layer of winter snow and observed in higher elevations. On the other hand, the boundary between them does not coincide with the snow line and is located at a lower elevation closer to the sea shore. Thus, correlation of these boundaries with the ELA is still not clear and further investigations are needed.

Comparison of King George Island maps in scale of 1:200 000 constructed from aerophotography data of 1956 with satellite images of the 1979 — 1992 period showed a noticeable (up to 1000 m in length and 2 km² in area in the case of Lange Glacier) retreat of 11 outlet glaciers during 36 years under regional climatic warming about 1°C during the last 50 years [Simões and Bremer, 1995].

Gоворуха и others (1974) found in 1970 a maximum ice thickness of 326 m for the western part of the King George Island ice cap (Fig. 2). A British Antarctic Survey found in 1975 thicker ice (357 m) about 4 km from the main ice divide, however, bedrock reflections were recorded only in some shorter sections of the flight (Fig. 2) because of strong scattering of VHF radio waves due to englacial inhomogeneities such as water inclusions, ice layers and lenses with different density and structure [Simões and Bremer, 1995]. On Nelson Island ice dome (area 156.6 km², maximal elevation 324, 6 m) the average and maximum ice thickness are 120 and 169 m, respectively [Ren and others, 1995].

Numerical simulations using two-dimensional ice flow and energy/mass balance models allowed to model satisfactory a steady-state condition for the King George Island ice cap and estimate its sensitivity to climate change [Knaps and others, 1995]; cooling or warming at 1°C leads respectively to 10% increase and to 36% decrease of ice volume. Furthermore, climate warming, according to IPCC-90 scenario leads to 55% ice volume...
decrease by 2100. Additional data are necessary to make the modelling results more reliable, including information on ice thickness and subglacial relief, in particular for drainage basins of outlet glaciers that exert strong influence on dynamics of the ice cap on the whole.

One of the basic aims of the field work was to obtain data on ice thickness and subglacial relief along the main ice divide of King George Island ice cap in order to choose a suitable site for deep ice core drilling and for studying the glacier structure and obtaining information about past glacioclimatic conditions. It was also supposed to carry out a more detailed radio echo sounding survey in the less crevassed upper part of the drainage basin of the outlet Lange Glacier (27.6 km²), including the area near the main ice divide where in December 1996 a 50 m deep borehole was drilled by a group of Argentinian, French, Brazilian and Chilian scientists. In this drainage basin it was also supposed to prepare a net of stakes for further mass balance and ice velocity measurements. However, only the first part of radio echo sounding program, i.e., the measurements along the main ice divide on King George Island was performed because of bad weather conditions.

Radar equipment and measurements
A monopulse radar designed specially for ground-based sounding of temperate glaciers up to 400 m thick was used in our studies. The radar had the following parameters: transmitted pulse duration of 0.25 μs, central frequency of transmitted signals of 40 MHz, transmitted output power of 2.5 kW, period of transmitted pulse repetition of 10 ms, sensitivity of receiver of 60 mV, bandwidth of receiver of 40 MHz, input DC voltage of radar equip-

ment of 12 V, total required current of 3 A, and total weight of 15 kg including antennas. Identical 1700-ohms resistively loaded dipoles of 5.8 m long with -10 dB antenna gain constructed as two separate plastic tubes of 3 cm and 2 cm in diameter were used as transmitting and receiving antennas. A portable oscilloscope and a portable magnetic tape-recorder were used for registration of received signals. The former was switched to the output of the receiver equipped by a logarithmic amplifier with input and output dynamical range of 80 dB and 30 dB, respectively, and by an input attenuator of 0 and -20 dB. The latter recorded radar signals converted by means of stroboscopic transformer to low frequency range. The precisely-known period of transmitted pulse repetition was used for timing calibration of radar records. Synchronizing of the transmitter and the receiver was provided by signals from the transmitting antenna, and synchronization level controlled by an indicator. As a result, the stable registration of radar information was provided in three regimes: visual, on film and on magnetic tape. In the field two or three complete wave forms were recorded on magnetic tape; recording process lasted 30 – 40 s and could be controlled by the sound signal tone. Each radar record was accompanied by a corresponding speech information. In a laboratory a special transformer was used to visualize these records on the paper tape.

Transmitting and receiving units with separate supply sources (12 V batteries with capacity of 55 Ah) were mounted on two Nansen sledges transported over the glacier "in line" by "Alpine II" snow-mobile (Fig. 3). Antennas were fixed on the sledges 0.3 m above the snow surface. In crevassed zones a coupling of two snow-
mobiles and two sledges was used; the last snow-mobile served as insuring one.

An optimal distance between transmitting and receiving antennas that provided a stable synchronization and an acceptable wave form after transmitted pulses was experimentally chosen before the beginning of a radar survey. The best wave form was observed when the distance between antennas centres was more than 20 m, but stable synchronization was kept at a distance of up to 12 m. Namely such arrangement of antennas was used during all radar measurements.

A satellite Global Positioning System (GPS) was used for positioning of radar measurement points with accuracy about ± 200 m. A series of control points at a distance of about 5 — 10 km from each other served for laying the radar profile; their coordinates were predetermined on a SPOT satellite image mosaic at a scale of 1:100 000. Glacier surface elevation at radar points were measured using a portable barometer with a accuracy of ± 20 m.

Measurements on the glacier were conducted from 8 to 20 December 1995. During 6 days with relatively good weather the radar measurements were carried out at 109 points situated at the distance of about 0.5 km over a 55 km long profile along the main ice divide on King George Island and crossing some outlet glaciers in their upper parts (Fig. 2).

Results of radar measurements

An example of an oscillogram and of a magnetic record collected in the western part of King George Island ice cap, at point 6, is shown in Fig. 4. On the oscillogram (Fig. 4a) a full record of received signals is presented; on the magnetic record (Fig. 4b) the initial part of the transmitted pulse 0.1 ms long is truncated because of strobing procedure. In all other points the character of both types of records is quite identical. Three groups of signals are distinguished on records: (1) transmitted pulses at the start of the scale have the constant form as two half-period (a result of double differentiation of transmitted signal when passing through receiving and transmitting antennas) and a constant duration (about 0.3 μs); (2) long-term signals with the maxima about 0.8, 1.7 and 2.5 μs; (3) bedrock and internal reflections. As a rule, bedrock reflections had a form close to transmitted signals, or differ from them by a number of half-periods and the ratio of their amplitudes due to spatial variations in total electromagnetic energy losses and in the character of bedrock, mainly its macrocrust. This criterion, together with small changes in delay time while replacing along the radar profile from point to point, served as the main one for distinguishing the bedrock reflections on oscillograms and magnetic records (Fig. 4).

At 78 measurement points (72 % of the total) bedrock reflections from depths to 250 — 300 m exceed noise and interference level are distinctly distinguished on enlarged oscillograms and look like as in Fig. 4; at nine points (eastward of Collins ice dome) internal reflections were also recorded. In the rest of the points the amplitude of bedrock reflections was confused with the receiver noise and could be distinguished only on the initial oscillograms (films).

When the radio echo-sounding is two-positioned (receiving and transmitting antennas are separated) and the upper and lower glacier boundaries are horizontal or parallel inclined, the following equation for calculating the ice thickness is valid [Macheret and others, 1993]:

$$h = \sqrt{\frac{V(t + L/c)/2}{2} - \left(\frac{L}{2}\right)^2},$$

where $V$ is an average radio wave velocity in glacier ice; $t$ is delay time of reflected signals from the bedrock measured by oscillogram; $L$ is the distance between the centers of receiving and transmitting antennas; $c$ is the radio wave velocity in the air. In our case, taking into account the properties of transmitting and receiving antennas, $t$ was calculated with reference to the first maxima of transmitted and reflected signals which were corresponded to maxima of transmitted and reflected electromagnetic energy; according to the data of radio waves velocity measurements in temperate glaciers [Macheret and others, 1993], value of $V$ is taken equal to 161 m/ms. Since the distance between the antennas is small ($L$=12 m), equation (1) with small loss in accuracy (not more than 4 m) can be replaced by a simpler one for one-positioned radar (with coinciding antennas):

$$h = Vt / 2.$$

The results of radar and barometric measurements on King George Island ice cap are presented in Fig. 5. Near the main ice divide the largest ice thicknesses are measured close to the summit of ice domes B and C, where they reach 317 and 327 m (points 34 and 78) being much larger than at points 5 and 6 (99 m and 82 m) at the top of Collins ice dome. In the upper parts of outlet glaciers between ice domes A and B (points 7 — 11), the ice thickness is 82 — 150 m and bedrock lowering is distinctly noticeable. In this area, between points 8 and 20, three internal reflection horizons at the depths intervals of 50 — 100, 95 — 265 and 130 — 135 m were found. In the upper part of outlet Lange Glacier, at the drill camp (point 32), near the top of ice dome B, the ice thickness is approximately 267 to 317 m. Between ice domes B and C (points 55 — 75) ice thickness varies from 140 to 300 m and at the final eastward point of profile located in the upper part of outlet glacier that flows northward to Drake strait, the ice thickness is about 190 m.

In general, subglacial relief repeats the glacier surface topography and is characterized by comparatively large bedrock irregularities with elevation changes of up to 50 — 100 m (Fig. 5). The similar subglacial relief is characteristic for many ice caps of Eurasian Arctic, in particular, for Svalbard [Macheret and Zhuravlev, 1985; Macheret and others, 1992] and Franz Josef Land [Dowdeswell and others, 1996].

Comparison of data obtained (Fig. 5) with previous data of Govorunhka and others (1974) and BAS [Simões and Bremer, 1995] (Fig. 2) taking into account possible
Differences in positioning of the radar profiles shows satisfactory coincidence for Collins ice dome (between points 1 and 8) and on the western slope of ice dome B (between points 20 and 50), excluding differences with data by Govorukha and others (1974) between points 8 — 15 and 32 — 36. It can be supposed that the differences between points 8 — 15 result from either coincidence of both radar profiles in position or from misinterpretation of internal reflections by Govorukha and others (1974); internal reflections recorded by us were taken for bedrock reflections. For two other areas on the western slope and near the top of ice dome B, the large differences can be related to incoincidence of radar profiles. The nature of those recorded internal reflections is not clear and further investigations are needed for their interpretation.

**Discussion and conclusions**

The main result of a ground-based radio echo-sounding survey carried out in December 1995 is a successful application of a portable monopulse radar (VIRL) with a central frequency of 40 MHz for sounding the temperate ice cap in King George Island and obtaining new data on the ice thickness along the main ice divide. These data show ice thicknesses of up to 327 m near the largest ice dome summits and the absence of abrupt bedrock rises in their top part as it followed from measurements by Govorukha and others (1974), and the important influence of outlet glaciers on subglacial bedrock topography.

Fig. 5 illustrates the contribution of outlet glaciers in the distribution of ice thicknesses on island ice caps. It indicates a close link between the area \( F \) \( (\text{km}^2) \) and radar-measured maximum ice thickness \( h_{\text{max}} \) \( (\text{m}) \) in Nordaustlandet, Franz Josef Land, Severnaya Zemlya and South Shetland Islands which belong to two basic groups: (1) without well-expressed net of outlet glaciers and (2) with wide-spread net of them. For these groups the coefficients of approximating functions in form \( F = a h_{\text{max}}^b \) are different.

![Graph](image-url)

**Fig. 5.** Results of ground-based radio echo-sounding along the main ice divide of King George Island ice cap collected with a monopulse radar in December 1995. 1 is glacier surface; 2 is glacier bottom, 3 are internal reflection horizons. Glacier surface elevations are measured by a portable barometer at points 1 to 32 and are taken from British map at scale of 1:200 000 at points 33 to 109.
$H_{\text{max}} = 61.861 F^{0.279}$ (correlation coefficient $r = 0.913$),

$H_{\text{max2}} = 64.218 F^{0.239}$ ($r = 0.992$),

where subscripts 1 and 2 denote ice caps of groups 1 and 2; variations between them defines the difference in maximum ice thickness of such ice caps.

According to data available (Macheret and Zhuravlev, 1985) the relationships between average ($H_{av}$) and maximal ($H_{\text{max}}$) ice thicknesses of Svalbard glaciers with (I) negative and (II) positive subglacial relief are following:

$H_{av}/H_{\text{max}} = 0.50 \pm 0.11$,

$H_{av}/H_{\text{max2}} = 0.64 \pm 0.13$.

Taking into account the relationships between area and maximum ice thickness of ice caps given in Fig. 6 and equations (5) and (6), an estimated average ice thickness of King George Island ice cap is about 180 – 230 m that is 55 – 70 m less than the average ice thickness of ice caps of the same area without outlet glaciers, result of the stretching out of ice masses to the sea through draining basins. Therefore, further studies of outlet glacier basins are very important to understand the general response of King George Island ice cap to climatic changes, and their influence should be taken into account in numerical models of the dynamics and evolution of the ice cap.

The studies performed allow us to choose the most appropriate sites for the deeper ice core drilling on King George Island ice sheet, namely, near the top of ice domes B and C where ice thicknesses are over 300 m (Fig. 5). Comprehensive glaciological study is planned for draining basin of the outlet Lange Glacier, including mass balance observations, ice velocity and ice thickness measurements, and bedrock morphology and bottom conditions investigations, providing data for testing mathematical models which describe the regime, dynamics and evolution of outlet glaciers. These studies would allow us to come closer to a quantitative estimation of response of subpolar ice caps to short-term environment changes in the south sub-polar region. It would be also important to solve analogous theoretical problems for Eurasian Arctic conditions, in particular, for Svalbard glaciers.

Analysis of satellite images in various wave length range will provide further information about area and volume changes of King George Island ice cap, about mass balance characteristics and about the main glaciological boundaries and ice formation zones.
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РЕЗЮМЕ

Обсуждаются результаты наземных радиолокационных исследований, выполненных в декабре 1995 г. вдоль главного ледораздела ледникового купола острова Кинг-Джордж с помощью радара мощностью 40 мВт. Работы были проведены российскими, бразильскими и чилийскими учеными в составе 41-й РАЭ и Международной гляциологической экспедиции, организованной Федеральной университетом Рио-Гранде до Сул, Бразилия, в рамках поддержанной СКАР Международной программы «Гляциология Южных Шетландских островов». Последняя ставит целью изучение современного состояния и эволюции субполлярных ледников в южной полярной области, оценку их реакции на короткопериодные изменения климата и вклад в текущие изменения уровня моря. Одна из главных задач полевых работ — получение данных о толщине льда вдоль главного ледораздела ледникового купола для выбора места глубокого кернового бурения.

Ясно идентифицируемые отражения от ложа с глубин до 327 м получены на 55-ом профиле. Вблизи вершин наиболее крупных куполов В и С — наиболее подходящих мест для глубокого бурения — измеренная толщина льда достигает 317 и 327 м, соответственно.

Анализ данных по максимальной и средней толщине льда и площади островных ледников куполов Евразийской Арктики (Северо-Восточная Земля, Земля Франца-Иосифа, Северная Земля) и Субантарктики (Южные Шетландские острова) и их космических изображений показал тесные корреляционные связи между этими характеристиками для ледниковых куполов с хорошо выраженной сетью выводных ледников и без нее.

Ледниковый купол острова Кинг-Джордж относится к первой группе; его средняя толщина составляет 180 — 230 м (объем 236 — 302 км³), что на 55 — 70 м меньше, чем для ледниковых куполов такой же площади, но не имеющих выводных ледников. Это может быть результатом «вытяживания» выводными ледниками дополнительных масс льда в море.