УДК 551.324.54

Observation of ice-flow vectors on inner-continental traverses in East Antarctica

© 2010 г. A. Richter[1], D.V. Fedorov[2], A.K. Dvoryanenko[2], S.V. Popov[3], R. Dietrich[1], V.V. Lukin[4], A.Yu. Matveev[2], M. Fritsche[1], V.P. Grebnev[2], V.N. Masolov[3]

[1]Technische Universität Dresden – Institut für Planetare Geodäsie, Dresden, Germany;
[2]ФГУП Аэрогеодезия, Санкт-Петербург; [3]Морская полярная геологоразведочная экспедиция, Санкт-Петербург;
[4]Российская антарктическая экспедиция, Санкт-Петербург

richter@ipg.geo.tu-dresden.de

Статья принята к печати 11 августа 2009 г.

GPS-observations, ice flow, inner-continental traverse, marker, surface geometry, velocity vector.
Вектор скорости, внутриконтинентальный траверс, геометрия поверхности, ГПС-измерения, репер, течение льда.

During the Antarctic field seasons 2006/07 and 2007/08, geodetic fieldwork was carried out along the continental traverses Mirny–Vostok and Progress–Vostok in East Antarctica. Based on repeated GPS observations, horizontal ice flow velocities were determined for 10 markers with accuracies in the mm a^{-1} level. The obtained vectors are in general consistent with the regional ice sheet geometry. A significant impact of subglacial water cavities on ice-flow dynamics is identified.

Во время Антарктических полевых сезонов 2006/07 и 2007/08 гг. геодезические полевые работы были проведены во внутриконтинентальных научных походах от обсерватории Мирный и от станции Прогресс до станции Восток. На основе повторных GPS-наблюдений горизонтальные скорости течения ледника были определенны для десяти реперов с точностью около 1 мм/год. Полученные векторы в основном совпадают с местной геометрией поверхности ледника. Установлено значительное влияние подлёдных водоёмов на динамику течения ледника.

Introduction

The knowledge of the flow velocity field at the ice surface is fundamental for the understanding of glacier dynamics and the base for crucial scientific questions like the present-day ice mass balance. Although satellite remote-sensing methods have been applied successfully for the determination of flow velocity fields for fast-flowing glaciers, ice-shelves and Antarctica's coastal regions [6], these approaches are not suitable for the particular conditions in the Antarctic inland. This is true especially for the vast East Antarctic ice sheet, which is on one hand of great importance for global ice mass balance estimates and future sea-level rise predictions, and on the other hand still lacking reliable information about the ice-flow dynamics over large regions.

Therefore, in-situ ice flow measurements are still indispensable and of particular value in the remote regions of the East Antarctic interior. Such observations can be realised in the frame of continental traverses. The worldwide most outstanding traverse is the sledge convoy of the Russian Antarctic Expedition that every year covers the 1,415 km from observatory Mirny to Vostok station and back. This traverse passes three former Soviet Antarctic stations Komsomolskaya, Vostok-1 and Pionerskaya and, in addition to the famous subglacial lake Vostok, two smaller subglacial lakes discovered near Komsomolskaya and Pionerskaya stations [7].

In the Antarctic field season 2006/07 one geodesist joined the scientific traverse and the convoy from Vostok back to Mirny station. Along the convoy route, a number of geodetic control markers were installed and observed for the first time with Global Positioning System (GPS) receivers. One year later, two geodesists joint the convoy and repeated the GPS observations on most of the control markers. In the Antarctic season 2007/08, an experimental convoy reached for the first time Vostok from Progress station. A geodesist participating in this outstanding operation was able to set up and observe a number of geodetic control markers along this traverse.

The area of investigation, covered by the two traverses and the control markers along them, is of particular glaciological and geo-scientific interest. In the sector of East Antarctica spanned by the stations Mirny, Vostok and Progress, such outstanding research objects like the subglacial lake Vostok, the Ridge B ice dome and the subglacial mountain range *podlednye gory Golitsyna* are situated. The location of the investigated area is shown in Fig. 1.

Here we present the first horizontal ice flow velocities obtained from precise GPS observations on the control markers along the Mirny–Vostok continental traverse.

Methods

We have used repeated geodetic GPS positioning on control markers to determine horizontal flow velocities of the ice surface at the marker locations.

One crucial issue is the design of the control markers. First, the markers must allow an exact self-centring of the GPS antennas in order to avoid systematic measurement errors. Second, the markers must assure a stable position both in the horizontal and in the vertical with respect to the snow layer

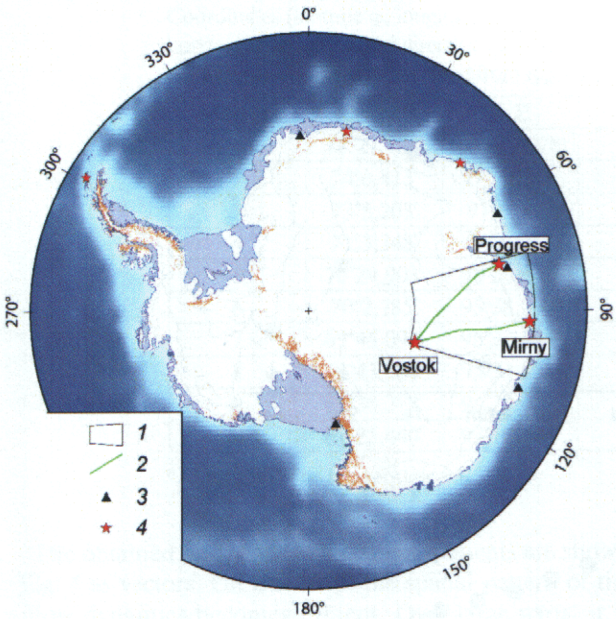

Fig. 1. Map of Antarctica and the area under investigation (*1*); *2* – continental traverses; *3* – GPS reference stations; *4* – Russian Antarctic stations

Рис. 1. Карта Антарктиды и район исследования (*1*); *2* – внутриконтинентальные траверсы; *3* – опорные станции GPS; *4* – российские антарктические станции

they are attached to. Third, the markers must allow finding and re-occupying them after one or more years taking into account the varying surface accumulation rates in the region under investigation. The specific logistic conditions on the scientific traverses have also to be considered. The markers used in the presented work, consist of aluminium tubes about 3 cm in diameter and 75 to 300 cm in length. Usually the tubes are plunged at least 50 cm deep into the snow. The shorter tubes were used only on the ice dome near Vostok station where accumulation is relatively low. They where plunged more than half their length into the snow and were supplemented by high bamboo stakes in order to mark the marker location. All the markers along the Vostok–Mirny traverse were found in immaculate state one year after their installation thus the applied signalization has proven effective.

During the observation sessions, GPS antennas were installed on top of the markers. The following types of GPS receivers were used: Trimble 4000SSi, Trimble R7, Leica 1200. All three utilized receiver types are geodetic two-frequency receivers and were set up to record raw GPS observation data (microwave codes and phases). In general, by using such instrumentation and the applied strategy, software and models for the data post-processing positioning accuracies of a few mm up to 1 cm can be achieved for the horizontal coordinate components. The vertical component is generally less accurately determined. The receivers were set up to a recording interval of 15 s and a horizon mask of 0°. The power supply was realised by 12 V gel accumulators, however, solar panels had to be employed to avoid freezing of the accumulators at air temperatures below –50°C.

On the Vostok–Mirny traverse, the markers were occupied usually for at least four hours of observation. On the experimental traverse Progress–Vostok, however, the logistic constraints often did not allow such long observation durations; some of the observations were as short as 30 min. The observation duration is crucial for the determination of accurate marker coordinates.

3D coordinates for each marker were obtained from a post-processing of the recorded GPS data. For this, the scientific Bernese GPS software v 5.0 [3] was used. The coordinate determination was based on the differential method, using a set of five permanent GPS stations of the global IGS network as reference. These reference stations are situated on bedrock evenly distributed around the Antarctic coast and are shown in Figure 1. In order to achieve the desired positioning accuracy in the order of 1 cm, satellite orbits as well as reference station coordinates and velocities of highest accuracy and homogeneity have to be introduced and state-of-the-art models to correct for disturbing atmospheric, tidal and other effects have to be applied. In this study, we used the products from a reprocessing of continuous GPS data of a global network starting in 1994 [10].

One challenge for the differential coordinate determination consists in the long baseline lengths between our markers and the reference stations in the order of 10^3 km. The differential coordinate determination was based on the GPS carrier signal phases. A specific problem in the phase observation analysis consists in the resolution of so-called ambiguities. In the Bernese software, several ambiguity solution strategies are implemented which yield different coordinate accuracies in dependence of the baseline length. However, these ambiguity solution strategies require for their success minimum observation duration, that is, a minimum geometrical change in the satellite constellation throughout the observation. Therefore, and because of the dependence on baseline length and other factors, the accuracy of the determined coordinates does not increase linearly with the observation duration. The accuracy of the East coordinate component solutions for the GPS

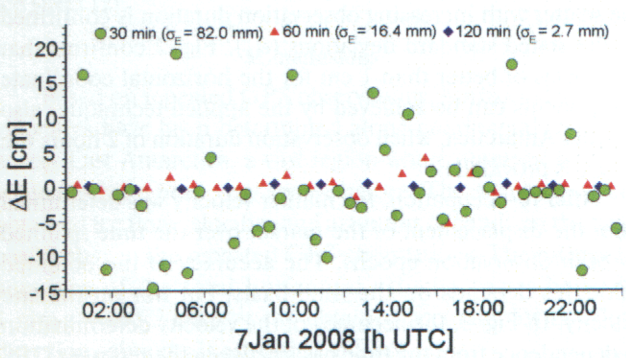

Fig. 2. GPS positioning error at Vostok station as a function of the observation duration (explanations in the text)

Рис. 2. Погрешность позиционирования GPS на станции Восток в зависимости от длительности наблюдения (объяснения см. в тексте)

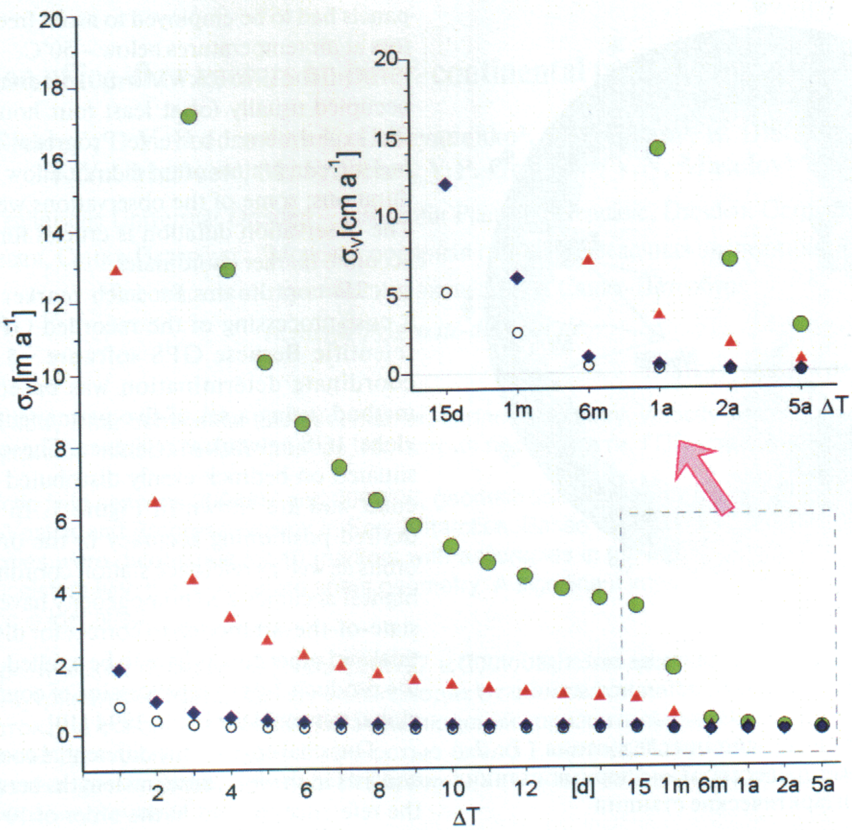

Fig. 3. Velocity determination error as a function of the time basis between repeated GPS observations (explanations in the text). The inset in the upper right corner is a zoom into the longer time bases

Рис. 3. Погрешность определения скорости в зависимости от периода времени между повторными GPS-наблюдениями (объяснения см. в тексте).
В верхнем правом углу – фрагмент участка более продолжительных периодов в увеличенном масштабе

marker at Vostok station as a function of the observation period is illustrated in Fig. 2: The GPS observations over 24 h on January 7, 2008 were split into independent segments of 30 min (grey dots), 60 min (red triangles) and 120 min (blue diamonds), which were processed independently. For each segment solution, the deviation ΔE in the East component from that of the 24 h solution is plotted. The reduction of the scatter with increasing observation duration is confirmed by the stated standard deviations (σ_E). Fig. 2 confirms that accuracies of better than 1 cm for the horizontal coordinate components can be achieved by the applied technique, also in inner Antarctica, when observation duration of 2 hours ore longer is provided.

After re-occupation, the marker velocity was determined from the displacement of the marker over the time spanned by both observation epochs. The accuracy of the obtained velocities depends on the time basis, but not on the site velocity. In Fig. 3, the accuracy of the velocity determination in dependence from the time basis between the repeated GPS observations is shown for different positioning accuracies. Assuming a positioning accuracy (Helmert positioning error) of 100 mm (grey dots, corresponding to 30 min observation durations, compare Fig. 2), 25 mm (red triangles, 60 min observations), 3.5 mm (blue diamonds, 120 min observations) and 1.5 mm (open circles, 24 h observations), the resulting total velocity error σ_v is shown for a time basis ΔT of 1, 2, ..., 15 days, 1 month, 6 months, 1 year, 2 years and 5 years.

The velocities resulting from the GPS data analysis refer initially to the global, geocentric reference frame IGb00 [8] that are represented by the five reference stations. For glaciological purposes, however, often the ice flow with respect to the basal bedrock is of greater interest. Therefore, we corrected the obtained horizontal ice flow vectors by the slight horizontal rotation of the Antarctic tectonic plate around an Euler pole located at 63.0°S, 234.7°E [4]. Thus, our final ice flow velocities are relative to the fixed Antarctic plate and hence relative to bedrock.

Details on the coordinate and velocity determination and the accuracy estimation are given in [11] and [9].

Results

From the processing and analysis of the repeated GPS observations, we obtained site velocities in the North and East components for 10 markers along the Mirny–Vostok traverse. In Table, the absolute flow velocities and flow directions are given for these markers along with the respective error estimates and marker coordinates.

Coordinates (latitude φ, longitude λ, ellipsoidal height H in the IGb00 reference system, epoch 2000.0), horizontal velocity v and direction (azimuth a) including accuracy estimates σ_v, σ_a for 10 markers along the Mirny–Vostok as determined from repeated GPS observations

Markers	φ, S	λ, E	H, m	V, m a^{-1}	$\pm\sigma_v$, mm a^{-1}	a
1	78°27,964'	106°49,978'	3478	1,996	1	133,66°
2	74°6,413'	97°29,911'	3502	2,290	2	50,46°
3	73°5,203'	97°1,005'	3412	2,463	1	36,73°
4	71°3,348'	96°4,667'	3000	9,434	1	23,69°
5	70°29,903'	95°50,638'	2859	7,423	7	38,89°
6	70°2,285'	95°38,598'	2798	4,496	2	45,00°
7	69°45,093'	95°32,446'	2752	2,062	2	25,04°
8	69°43,584'	95°31,835'	2748	2,174	3	18,04°
9	68°38,372'	94°27,079'	2265	12,455	16	349,96°
10	67°25,440'	93°17,444'	1461	40,064	4	8,263°

*At all markers $\pm\sigma_a$ equals 0.05°.

The obtained horizontal velocity components are shown in Fig. 4 as vectors. On this map, the spatial pattern of the ice flow dynamics becomes evident. Over large parts, it is consistent with the regional ice surface elevation and slope. The markers situated on high elevations where topographic gradients are weak exhibit very small flow velocities. The further down the ice dome towards the coast, the absolute velocities generally increase. The markers along the Mirny–Vostok traverse move to NE, the marker at Vostok station, however, move to SE.

A remarkable feature is the ice flow vectors obtained for two markers near the former Pionerskaya station. The absolute flow velocity at these sites is considerably reduced compared to the neighbouring markers. This might be explained by the topographic impact of the *podlednye gory Golitsyna*. Moreover, the flow vector changes significantly between the two markers over a distance of only 3 km (see Fig. 4, top). This result suggests that the subglacial Lake Pionerskoe [7] plays an important role on the ice flow dynamics on local scales.

A comparison of our results with earlier geodetic flow velocity determinations could be interesting in two aspects. On the one hand it may document the increase in the observation accuracy over the last decades, on the other hand significant differences might indicate changes in the ice flow regime, for example as a possible consequence of recent climate changes. Before the availability of GPS, one method for the determination of absolute flow velocities consisted in the repeated determination of local coordinates with respect to reference points on bedrock by classical triangulation. By the means a geodetic profile along the first 100 km of the convoy route Mirny–Vostok was observed in 1962 and 1965 [1]. The final, southernmost marker of that profile coincides with the location of the northernmost control marker in Table (last line). The comparison of our velocity vector with the results from the 1960's (v = 38.2 ± 3.2 m a^{-1}, a = 10 ± 7°) shows, that the local ice flow velocity at this point has not changed significantly over the last 40 years. Beyond the 100 km profile a significant determination of absolute flow velocities by triangulation was very difficult because the measurement errors accumulate with increasing distance from the fix reference points (bedrock markers, only at the coast) while the flow velocities decrease rapidly with increasing distance from the coast. Therefore, an attempt was made to determine the ice flow velocity vector at Vostok station by repeated astro-geodetic coordinate determinations beginning in 1963 [6]. In this way, a velocity of v = 3.7 ± 0.7 m a^{-1} and an azimuth of a = 142 ± 10° were obtained. The difference with respect to the result presented here (first line in Table) must be attributed essentially to systematic uncertainties of the astro-geodetic coordinate and velocity determination. Although the relative velocity error reached in this case 85 % this example suggests that velocity determinations in the Antarctic interior were possible with an accuracy of a few m a^{-1} even without satellite-geodetic techniques. More details on the astro-geodetic velocity determination at Vostok, as well as a comparison of our results with those of several other recent investigations are given in [11].

It is important to note that the velocities obtained here refer to the ice/snow surface. They are therefore not comparable with flow velocities inferred from inclinometer measurements in boreholes for different depth layers of the ice sheet [2].

Conclusions

Based on repeated GPS observations, horizontal ice flow velocities have been determined along continental traverses across East Antarctica, a vast region where observed ice flow velocities have been very sparse before. The accuracy of the obtained ice flow velocities and azimuths depends on the time basis between the repeated GPS observations. The estimated accuracy of the total horizontal velocity varies between 1 mm a^{-1} and 2 cm a^{-1}; the obtained accuracy for the flow direction azimuths is estimated at 0.05°.

Our results show, that subglacial water cavities, even of small spatial extension, influence the ice-flow dynamics significantly. A better understanding of the mechanism of the glacier flow over a limited water surface like subglacial Lake Pionerskoe requires further, systematic investigation including

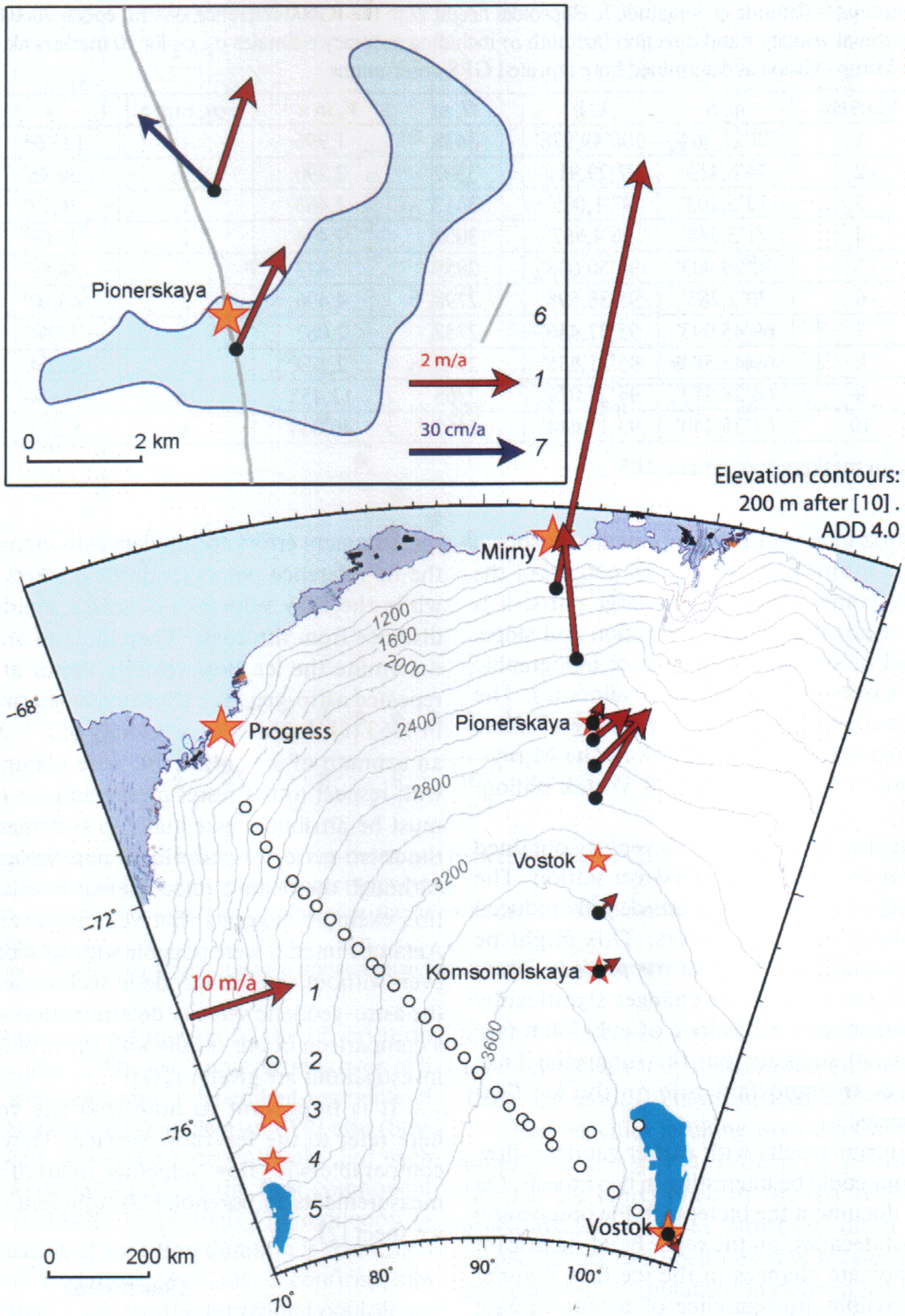

Fig. 4. Ice flow velocity vectors (*1*) as determined from repeated GPS observations on control markers.
Top: zoom of the Pionerskaya station area; *2* – control markers Progress – Vostok; *3*/*4* – present/former Antarctic stations; *5* – subglacial lake according to [7]; *6* – convoy route; *7* – residual vector of the northern marker minus velocity components of the southern marker (note the different scale)

Рис. 4. Векторы скоростей течения ледника (*1*), определёные с помощью повторных GPS-наблюдений на реперах.
Вверху: увеличенный фрагмент района станции Пионерская; *2* – реперы на профиле Прогресс – Восток; *3*/*4* – действующие/недействующие антарктические станции; *5* – подлёдное озеро, по [7]; *6* – трасса санно-гусеничного похода; *7* – результирующий вектор северного репера после вычитания составляющих скорости южного репера

the extension and densification of the control marker network in the Pionerskoe lake region.

The presented ice flow vectors provide a valuable basis for the validation and improvement of numeric ice flow models as well as for the inference of velocity fields by satellite imaging techniques. Furthermore, they allow to direct future geophysical profiling along ice-flow lines and to adjust glaciological fieldwork to particularities of the ice-flow dynamics, which allows a more detailed interpretation of the data to be obtained. Reliable ice flow velocities are a crucial element in the assessment of the mass balance of the Antarctic ice sheet – one of the most pressing questions to glaciology in Antarctica at present.

The presented work is a Russian–German contribution to the International Polar Year 2007–2008 (IPY), in particular to the IPY project TASTE-IDEA.

Acknowledgement. We thank the participants of the Mirny–Vostok and Progress–Vostok convoys in the 52nd and 53rd RAE field seasons for their great support of the fieldwork, especially V.R. Voronin, V.E. Davydov, M.V. Vasiliev, P.P. Ivanov, V.A. Zyvarev, A.V. Sayzev, A.N. Pinyagin, V.V. Olefir. This work was partly funded by Deutsche Forschungsgemeinschaft DFG.

References

1. *Либерт И., Леонхардт Г.* Астрономические наблюдения для определения движения льда в районе станции Восток // Информ. бюлл. Советской антарк. экспедиции. 1973. № 88. С. 68–70.

2. *Марков А.Н.* Отличие динамики поверхности ледникового покрова Восточной Антарктиды в интервале глубин 0–200 м от динамики нижележащей толщи льда // МГИ. 2007. Вып. 102. С. 12–22.

3. *Dach R., Hugentobler U., Fridez P., Meindl M.* Bernese GPS Software version 5.0, Astron. Institute, University of Bern, Switzerland, 2007.

4. *Dietrich R., Rülke A., Ihde J., Lindner K., Miller H., Niemeier W., Schenke H.-W., Seeber G.* Plate kinematics and deformation status on the Antarctic Peninsula based on GPS // Global Planetary Change. 2004. V. 42. P. 313–321.

5. *Dittrich G., Schwarz G.* Die geodätischen Arbeiten der deutschen Gruppe während der 7. Sowjetischen Antarktisexpedition 1962, DKGG. 1965, III/5.

6. *Horwath M., Dietrich R., Baessler M., Nixdorf U., Steinhage D., Fritzsche D., Damm V., Reitmayr G.* Nivlisen, an Antarctic ice shelf in Dronning Maud Land: Geodetic-glaciological results from a combined analysis of ice thickness, ice surface height and ice flow observations // Journ. of Glaciology. 2006. V. 52. № 176. P. 17–31.

7. *Popov S.V., Masolov V.N.* Forty-seven new subglacial lakes in the 0–110°E sector of East Antarctica // Journ. of Glaciology. 2007. V. 53. № 181. P. 289–297.

8. *Ray J., Dong D., Altamimi Z.* IGS reference frames: Status and future improvements GPS // Solutions. 2004. V. 8. № 4. P. 251–256, doi:10.1007/s10291-004-0110-x.

9. *Richter A., Popov S.V., Dietrich R., Lukin V.V., Fritsche M., Lipenkov V.Y., Matveev A.Y., Wendt J., Yuskevich A.V., Masolov V.N.* Observational evidence on the stability of the hydro-glaciological regime of subglacial Lake Vostok // Geophys. Research Letters. 2008. V. 35. L11502, doi:10.1029/2008GL033397.

10. *Rülke A., Dietrich R., Fritsche M., Rothacher M., Steigenberger P.* Realization of the Terrestrial Reference System by a reprocessed global GPS network // Journ. of Geophys. Research. 2008. V. 112. B08403, doi:10.1029/2007JB005231.

11. *Wendt J., Dietrich R., Fritsche M., Wendt A., Yuskevich A., Kokhanov A., Senatorov A., Lukin V., Shibuya K., Doi K.* Geodetic observations of ice flow velocities over the southern part of subglacial Lake Vostok, Antarctica, and their glaciological implications // Geophys. Journ. Intern. 2006. V. 166. P. 991–998, doi: 10.1111/j.1365– 246X.2006.03061.x.

Наблюдения за векторами движения льда во внутриконтинентальных траверсах по Восточной Антарктиде

Знание поля течения ледника – основа понимания его динамики, что крайне важно для решения многих фундаментальных проблем, таких, например, как расчёт современного баланса массы льда. Методы дистанционного зондирования, которые позволяют определить скорости течения быстрых ледников в краевых частях Антарктиды, неприменимы для специфических условий внутренних районов Восточной Антарктиды. Поэтому основой получения данной информации служат полевые наблюдения векторов скорости течения ледника. Особенно важны они в данном регионе, где подобные единичные измерения выполнялись очень давно. Проведение таких полевых наблюдений стало возможным благодаря возобновлению научных внутриконтинентальных походов Российской антарктической экспедиции.

В ходе двух полевых сезонов 2006/07 и 2007/08 гг. в санно-гусеничных научных походах от станции Восток к обсерватории Мирный и от станции Прогресс к станции Восток были установлены реперы, на которых выполнены геодезические GPS-наблюдения с целью определения горизонтальных скоростей течения ледника. В настоящей работе впервые представлены векторы горизонтальных скоростей, полученных на основе повторных высокоточных GPS-наблюдений на десяти реперах, расположенных по трассе Мирный – Восток.

Применяемая методика наблюдений и обработки данных GPS позволяет определить горизонтальные компоненты координат с точностью до нескольких миллиметров в том случае, если длительность наблюдений составляет более 2 часов. Векторы скорости определялись посредством сравнения координат, полученных в ходе повторных наблюдений на идентичных реперах. Точность полученных компонентов скорости зависит от периода времени между повторными наблюдениями. Погрешность определения скорости течения ледника составляет от 1 до 20 мм/год и 0,05°.

Полученные векторы в основном совпадают с региональной геометрией поверхности ледника. Наши результаты в районе подлёдного озера Пионерское доказывают значительное влияние подлёдных водоёмов на динамику течения ледника. Сравнение данных, полученных для самого южного репера, с результатами 1960-х годов однозначно указывает на то, что в рамках названных погрешностей локальный режим течения ледника за последние 40 лет существенно не изменился. Представленные данные позволяют проверить и улучшить существующие гляциодинамические модели.