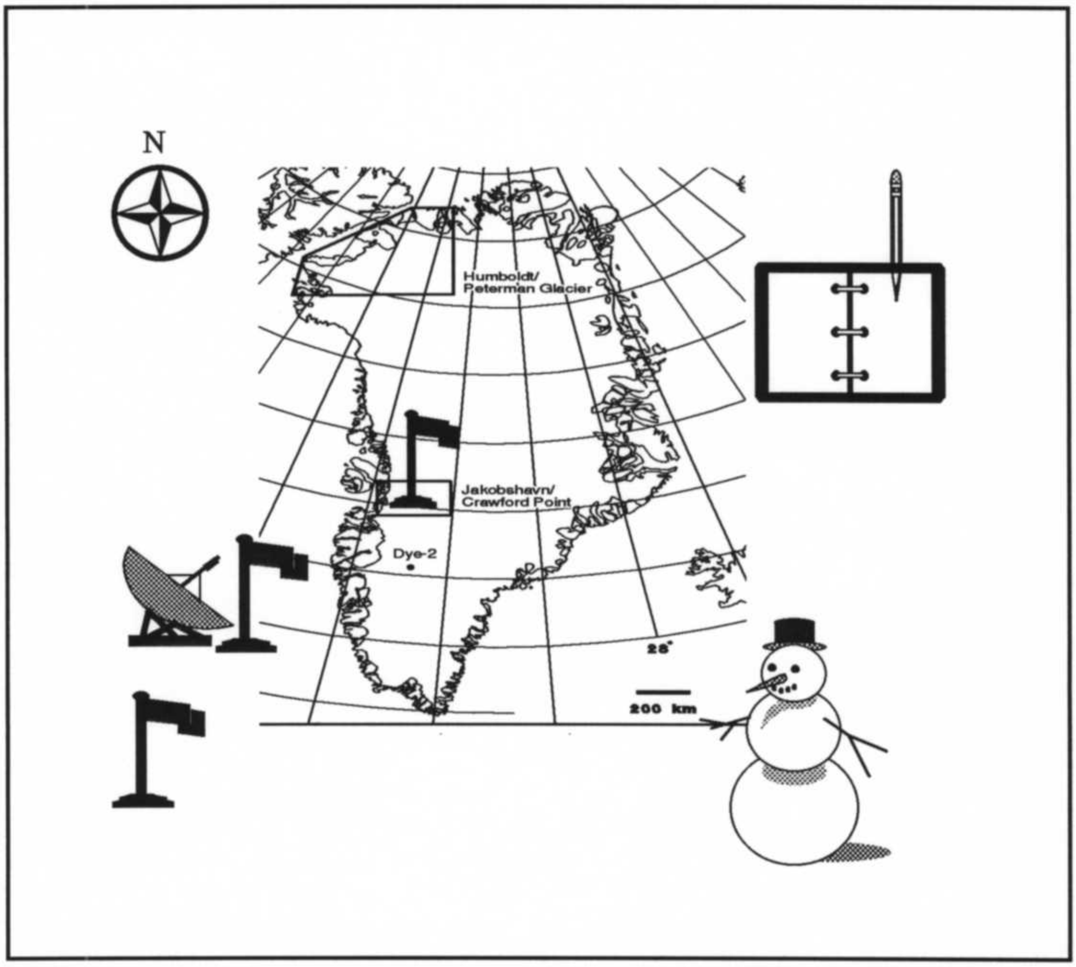
Greenland Ice Sheet Mapping with Optical Leveling and Global Positioning System



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BPRC Technical Report Number 94-03

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Greenland Ice Sheet Mapping with Optical Leveling And Global Positioning System

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BPRC Technical Report Number 94-03
ISSN: 1056-8050

Compiled in 1994 by the
Byrd Polar Research Center

This report may be cited as:

Sohn, H.G, Jezek, K.C, Thomas, R.H., Kuivinen, K., and Csatho, B. 1994. *Greenland Ice Sheet Mapping with Optical Leveling and Global Positioning System*. BPRC Technical Report 94-11, Byrd Polar Research Center, The Ohio State University, Columbus, OH, 98 pages.

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1. Introduction

In August of 1991 and June of 1992, conventional leveling was done to measure surface topography along a 40 km line located on the western flank of the Greenland Ice Sheet. Data were collected by R.H. Thomas, K. Kuivinen, and K. Jezek in 1991 and by R.H. Thomas, K. Kuivinen, P. Gogineni, D. Anderson, and K. Jezek in 1992. Leveling measurements were carried out in conjunction with surface Global Positioning System (GPS) measurements to serve as an independent control site for future airborne and spaceborne altimetry experiments. Level line elevations were adjusted to an absolute datum using one of our surface GPS observations. This reduced absolute coordinate of leveling data can be used to compare other surface elevation measurement methods such as the Airborne Oceanographic Lidar (AOL) instrument. Analysis of the leveling data yield a highly accurate estimate of relative ice sheet elevation above the geoid. Elevation above the ellipsoid can be estimated tying the level data to a derived GPS datum and adjust the remaining level data with a geoid model. In addition to surface elevation, data on ice sheet surface relief and accumulation rate are reported.

2. Approach

The purpose of land surveying is to measure elevations and distances between the leveling instrument and back and fore stadia rod sites. Figure 1 shows how the relative surface elevation can be computed. Here B.S. = Back Sight, F.S.= Fore Sight, E.I.=Elevation of Instrument, and

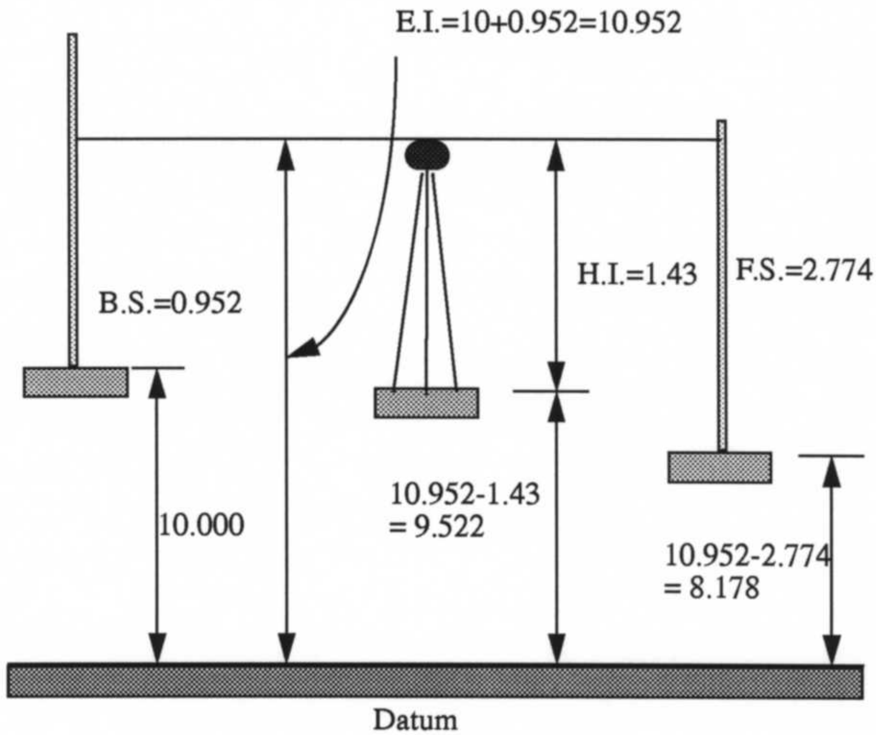

Figure 1. Leveling

H.I.= Height of Instrument. The following is an example calculation:

1) The height of our reference point (Back Sight) is 10.000 (m).
2) Measured values
Back Sight = 0.952 (m)
Height of Instrument =1.43 (m)
Fore Sight = 2.774 (m)
3) Calculated values (see Figure 1)
Elevation of Instrument = 10.000 + 0.952 = 10.952 (m)
Elevation of the surface at the instrument = 10.952 - 1.43 = 9.522 (m)
Elevation of the surface at the Fore Sight = 10.952 - 2.774 = 8.178 (m)

The distances between the instrument and the Back and Fore Sight are computed as follows (see Figure 2). In Figure 2, T.G. = Top Graticule, B.G.= Bottom Graticule, and C.G.= Center Graticule. This shows the leveling instrument configuration. The equation to calculate the distances is:

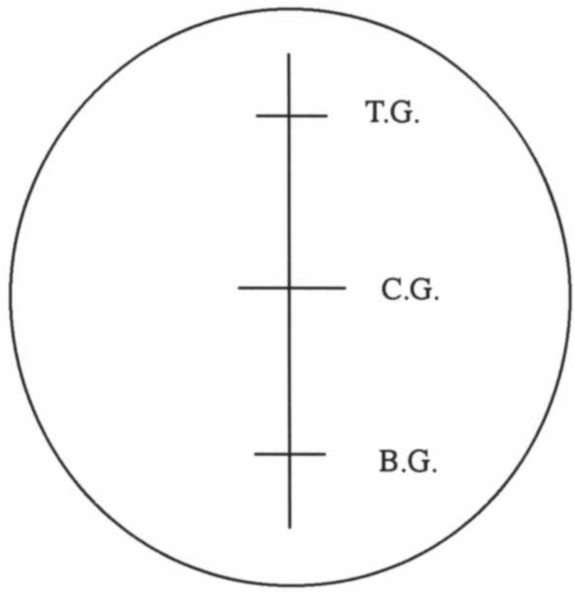

Figure 2. Leveling Instrument

$$L = K \times (TG - BG) \tag{1}$$

Here, L= distance between instrument and B.S. or F.S.

K= stadia factor (usually K=100). In our case and for the accuracies we required, K was determined experimentally for our instrument.

If either TG or BG is not available, then we can calculate L as follows:

$L = 2 \times (CG - BG) \cdot K$, when TG is not available;

$L = 2 \times (TG - CG) \cdot K$, when BG is not available.

As can be seen in Equation (1), the stadia factor K determines the distance between the instrument and the Back and Fore Sights. In the next section we will discuss the selection of an appropriate K for our leveling instrument.

3. Calculation of elevations and distances

3.1. Calculation of Stadia Factor K

Leveling and surface GPS observations were acquired along intersecting transects shown in Figure 3. (*) indicates the location of GPS receivers. In 1991 leveling was done along the S10-

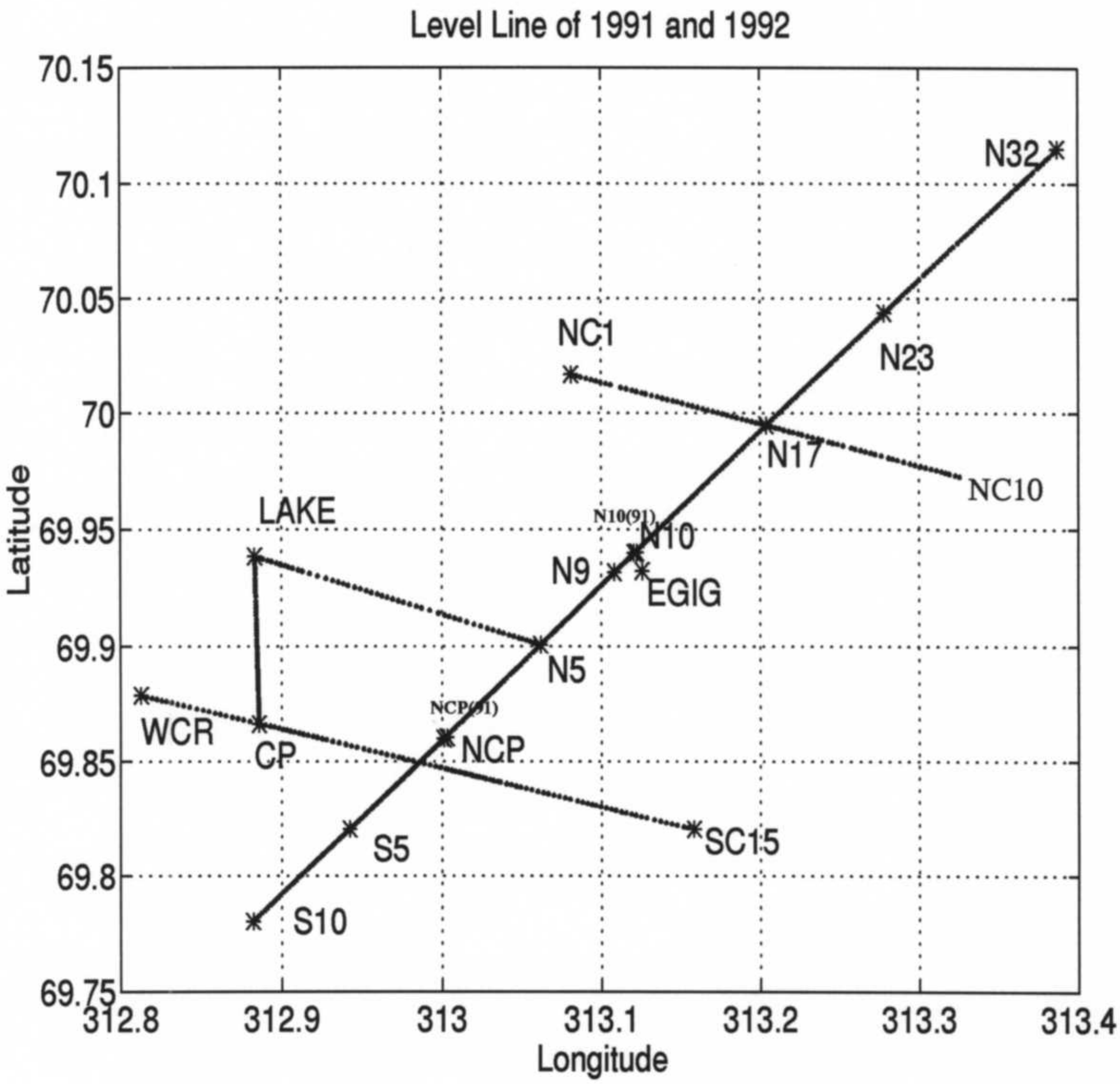

Figure 3. Level line of 1991 and 1992 data set

N32 line and GPS receivers were placed at NCP (91) and N10 (91). In 1992 leveling was done along the S10-N32, NC1-NC10, N5-CP, and WCR-SC15 lines. From the GPS measurements the location of the surface GPS antennas can be obtained. Surface GPS location is referred to latitude, longitude, and ellipsoidal height above the WGS 84. Table 1 shows the results of 1991 and 1992 surface GPS measurements. These results are the location of surface GPS antenna. The GPS antenna locations are offset from the location of aluminum and bamboo poles used as surface reference markers listed in Table 2. Every offset is taken to be along the level line.

Table 1: 1991 and 1992 GPS measurement

Station ID	Latitude	Longitude	Ellipsoidal Height of GPS Antenna (WGS84) [m]
NCP (91)*	69-51-37.24807	313-0 -10.530149	1992.055
N10 (91)	69-56-24.165055	313-7 -20.206515	1991.3695
NCP	69-51-36.16240	313-0 - 3.83350	1991.3946
S10	69-46-48.93591	312-52-56.16160	1933.1753
WCR	69-52-43.83255	312-48-46.38034	1942.9803
S5	69-49-14.07862	312-56-32.33451	1929.3577
N9	69-55-53.97171	313-6 -29.98330	1972.8011
N17	69-59-41.37001	313-12-13.32535	2055.5494
N23	70-2 -37.48100	313-16-41.12578	2089.6162
N32	70-6 -53.86224	313-23-12.70846	2114.0406
SC15	69-49-13.64865	313-9 -29.04098	2021.5423
NC1	70-1 - 0.35722	313-4 -52.20615	2036.4742
N10	69-56-23.34105	313-7 -13.88732	1989.5495
EGIG	69-55-55.09175	313-7 -32.67263	1982.3284
N5	69-54- 2.51030	313-3 -42.69045	2001.4303
LAKE	69-56-18.02381	312-53- 0.30083	1972.5013
CP	69-51-58.53962	312-53- 9.76962	1942.3909

*. (91) means 1991 measurement and the others are 1992 measurements
This is true for all other cases in this document.

Table 2: NASA Greenland leveling traverse: GPS antenna offsets

Station ID	Offsets
New Crawford Point (8-26-91)	Antenna on top of lower section of aluminum pole (antenna of north line is 75cm high and south line is 64cm high above the surface)
N10 (8-25-91)	Antenna on the snow surface, 154cm SSW of the aluminum pole
NCP (6-5-92)	Antenna on the snow surface, 318cm SSW of the aluminum pole
NC10 (6-14-92)	Antenna on the snow surface, 245cm East of aluminum pole
NC1 (6-14-92)	Antenna on the snow surface, 259cm West of aluminum pole
S10 (6-6-92)	Antenna on the snow surface, 387cm SSW of aluminum pole
WCR (6-6-92)	Antenna on the snow surface, 256cm West of WCR
S5 (6-7-92)	Antenna on the snow surface, 270cm SSW of aluminum pole
N9 (6-7-92)	Antenna on the snow surface, 230cm NNE of aluminum pole
N17 (6-8-92)	Antenna on the snow surface, 256cm NNE of aluminum pole
N23 (6-8-92)	Antenna on the snow surface, 222cm NNE of aluminum pole
N32 (6-9-92)	Antenna on the snow surface, 278cm NNE of aluminum pole
SC15 (6-13-92)	Antenna on the snow surface, 170cm East of aluminum pole
N10 (6-16-92)	Antenna on the snow surface, 133cm NNE of aluminum pole
Prasad Point (6-19-92)	Antenna on the snow surface, antenna at PP
Old Crawford Point Corner Reflector (6-19-92)	Antenna on the snow surface,198cm North of aluminum pole

To calculate the distance between GPS stations, the Vincenty Program* was used. The results are shown in Table 3. The Vincenty program solves the direct problem (i.e. given coordinates of one point and distance and azimuth to a second point, the coordinates of the second point and the azimuth to the first point are computed) and inverse problem (i.e. given coordinates of two points, the distance between them and the azimuths at the two points are computed) for any length lines. The results are compared with the distances calculated from the leveling (Table 4).. The

Table 3: Distances between GPS Receiver Stations

From	To	Forward Azimuth	Distance along the ellipsoid (m)
NCP (91)	N10 (91)	27-11-42.05382	10001.36
NCP	S5	207-12-16.29646	4949.43
NCP	S10	207-15-41.82881	10007.99
NCP	N5	27-12-42.31233	5100.89
NCP	N9	27-12-33.83762	8987.42
NCP	N17	27-13-2.26449	16922.76
NCP	N23	27-13-33.50831	23074.16
NCP	N32	27-13-6.56738	32032.27
N5	LAKE	301-37-50.04044	8026.55
LAKE	CP	179-16-47.26735	8041.81
WCR	CP	116-30-0.21950	3141.87
WCR	SC15	115-58-14.09004	14787.92

results of Table 4 are obtained by using K factor = 100. These distances are along the leveling surface, not along the ellipsoid. To compare the GPS and leveling derived distances, we have to have the same reference system. In this paper the distances along the ellipsoid (WGS84) calculated by Vincenty program have been extrapolated to the distances along the leveling surface. This scheme is represented in Figure 4. Here the terrain along the leveling surface is assumed smooth. From Figure 4 we approximate the surface distance as:

$$D' = D \times (a + (h_1 + h_2)/2)/a \qquad (2)$$

Where, a= 6378136 (m) in the case of WGS84;

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*. Richard H. Rapp, Geometric Geodesy Part II, Department of Geodetic Science and Surveying, 1989, pp 47-56.

h_1, h_2 = ellipsoidal heights above the ellipsoid;
D = distance along the ellipsoid (WGS84);
D' = distance along the surface.

Table 4: Distances from the surface leveling (K=100)

From	To	Distance along the surface (m)
NCP (91)	N10 (91)	10027.10
NCP	S5	4951.10
NCP	S10	10022.70
NCP	N5	5107.50
NCP	N9	8995.90
NCP	N17	16949.40
NCP	N23	23114.80
NCP	N32	32087.40
N5	LAKE	8038.40
LAKE	CP	8056.60
WCR	CP	3148.10
WCR	SC15	14788.20

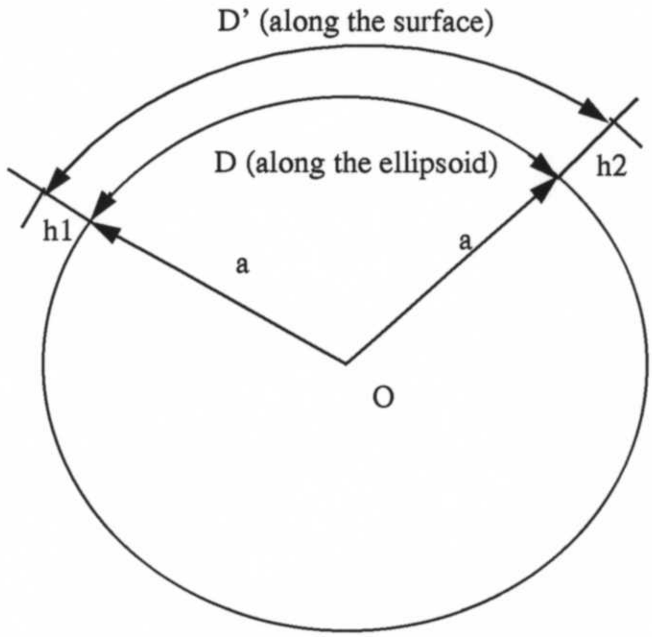

Figure 4. Surface Reduction Scheme

Comparisons between the GPS distances extrapolated to the surface and the leveling distances along the surface are given in Table 5. From this result, the estimated K factors are calculated. One must be careful to consider the GPS antenna offsets mentioned in Table 2. One example of a K factor calculation taking into account the GPS antenna offset is given in the following.

NCP (91) ellipsoidal height: 1990.855 (m) N10 (91) ellipsoidal height: 1991.3695 (m) reduced GPS distance along the surface = (10001.36)*(a+1991.11225)/a + **1.54**[*] = 10004.48 + **1.54** = 10006.02 where, 1.54 (m) is the antenna offset Thus K factor = 99.7897

*. This is the GPS antenna offset

Table 5: K factor computation

From	To	reduced GPS distance*	surface leveling distance	K factor
NCP (91)	N10 (91)	10006.02	10027.10	99.7898
NCP	S5	4951.44	4951.10	100.0069
NCP	S10	10010.38	10022.70	99.8771
NCP	N5	5099.31	5107.50	99.8396
NCP	N9	8984.73	8995.90	99.8758
NCP	N17	16922.39	16949.40	99.8406
NCP	N23	23076.14	23114.80	99.8327
NCP	N32	32036.62	32087.40	99.8417
N5	LAKE	8029.05	8038.40	99.8837
LAKE	CP	8046.26	8056.60	99.8717
WCR	CP	3142.82	3148.10	99.8323
WCR	SC15	14788.26	14788.20	100.0004

*. this distance is considered GPS antenna offsets

By averaging all these K factors, we determined our final K factor to be $K = 99.8744 \pm 0.0658$.

The following scheme is used to estimate error in distance. From Equation (1)

$$dL_i = (TG - BG)_i dK + Kd(TG) - Kd(BG) \tag{3}$$

$$dL_i = \begin{bmatrix} (TG - BG)_i & K & -K \end{bmatrix} \begin{bmatrix} dK \\ d(TG) \\ d(BG) \end{bmatrix} \tag{4}$$

From the above calculation of the K factor, we assume that the accuracy of K is 0.0658. The accuracy of the top and bottom graticule reading is taken as 1 mm. From the law of error propagation, the dispersion dL_i is as follows:

$$D\{dL_i\} = \begin{bmatrix}(TG-BG)_i K & -K\end{bmatrix} D\left\{\begin{bmatrix}dK \\ d(TG) \\ d(BG)\end{bmatrix}\right\}\begin{bmatrix}(TG-BG)_i \\ K \\ -K\end{bmatrix} \quad (5)$$

Where D{ } means dispersion (or variance) of the variable. Since there is no correlation between K and reading of the graticules, the following is obtained.

$$D\left\{\begin{bmatrix}dK \\ d(TG) \\ d(BG)\end{bmatrix}\right\} = \begin{bmatrix}0.0658^2 & 0 & 0 \\ 0 & 1(mm)^2 & 0 \\ 0 & 0 & 1(mm)^2\end{bmatrix} \quad (6)$$

By using the leveling data of 1991 and 1992, $D\{dL_i\}$ is obtained. The calculation procedure is summarized as follows;

1) Use 728 observations which have TG and BG.

2) Calculate average of $(TG-BG) = \frac{\sum (TG-BG)_i}{728}$ =1.3469 m

3) Calculate average distance with the derived K factor $L_{avg} = \frac{\sum [(TG-BG)_i \times 99.8744]}{728}$

4) Calculate $D\{dL_i\}$ by using above equation

$$D\{dL\} = \begin{bmatrix}1.3469 \times 1000\,(mm) & 99.8744 & -99.8744\end{bmatrix}\begin{bmatrix}0.0658^2 & 0 & 0 \\ 0 & 1(mm)^2 & 0 \\ 0 & 0 & 1(mm)^2\end{bmatrix}\begin{bmatrix}1.3469 \times 1000\,(mm) \\ 99.8744 \\ -99.8744\end{bmatrix}$$

$$= 2.7804 \times 10^4 mm$$

$$\therefore \sigma_L = 166.7464 mm$$

5) From the above result

$$L_{avg} = 134.519 \pm 0.167 m \text{ for a single observation} \quad (7)$$

Over 40 km the error is estimated as

$$\sqrt{\frac{40,000}{134.519}} \bullet 0.167 \text{ m} = \pm 2.88 \text{ m}$$

3.2 Reduction of Elevations and Distances

The raw land surveying data of 1991 and 1992 are listed in the Appendix B and are used to calculate elevations and distances between back sight, instrument, and foresight location. To calculate elevations, the scheme shown in Figure 1 is used. The distances between back sight and fore sight and instrument are calculated by using Equation (1). K=99.8744 is used instead of K=100.

3.3. Reduction of Latitude, Longitude and Ellipsoidal Height

The Vincenty program is used to calculate the latitude and longitude of the leveling site. To calculate absolute elevation, one GPS derived ellipsoidal height (WGS 84) is used. The relative elevations of the other points are calculated by using this reference point elevation. N10(91) and N10(92) are used for the reference points of absolute elevation in 1991 and 1992, respectively. One must note that the location of the GPS antenna and the location for the aluminum pole are not the same (see Table 2). Considering this, we calculate a new NCP location for 1992. The new latitude and longitude of NCP 92 are 69-51-36.25366, 313-0-3.96968. The location of GPS NCP(91) and new NCP (92) are used for reference latitude and longitude.

The reference elevation for 1991 leveling starting at N10 is 1991.370(m) above the WGS84 ellipsoid. The reference elevation of 1992 (N10) is 1989.550 (m) above the WGS84 ellipsoid. The reason for not using NCP(91) and NCP(92) as refererence elevation points is that there is a big bump around NASA camp which is very close to NCP (see Figure 5). Figure 5 has been created by using AOL data. The elevation difference (11cm) in NCP(91) between north and south line is thus regarded as a local change.

To compute the latitude and longitude of the leveling point, forward azimuth between two reference points is needed. Table 6 summarizes these forward azimuths and distances between two GPS points. One matter of concern is that the Vincenty program calculates the latitude and longitude of a point using distances along the ellipsoid. When we calculate the latitude and longitude of a point, we have to reduce the distance into the ellipsoid taking into account the ellipsoid height. This is summarized in the following equation (see Figure 4):

$$D = \frac{a}{h+a}D', \tag{8}$$

where $h = (h_1 + h_2)/2$;

D = distance along the ellipsoid;

D' = distance along the surface;

a = 6378136 (m) in WGS84 ellipsoid.

The plots of level line of 1991 and 1992 are in Appendix A. The reduced results of the latitude, longitude and ellipsoidal height are listed in Appendix C.

Table 6: Forward Azimuth Between two GPS points

.From	To	Distance	Forward Azimuth
NCP (91)	N10 (91)	10001.36	27-11-42.05382

Table 6: Forward Azimuth Between two GPS points

.From	To	Distance	Forward Azimuth
NCP	S5	4949.43	207-12-16.29646
S5	S10	5058.56	207-15-44.38540
NCP	N5	5100.89	27-12-42.31233
N5	N9	3886.53	27-15-48.21648
N9	N10	1023.02	27-9-50.90102
N10	N17	6912.33	27-21-45.07498
N17	N23	6151.40	27-26-24.64325
N23	N32	8958.11	27-27-34.03665
N17	NC1	5279.54	297-40-45.77992
N5	LAKE	8026.55	301-37-50.04044
LAKE	CP	8041.81	179-16-47.26735
WCR	CP	3141.87	116-30-0.21950
CP	SC15	14787.92	115-58-14.09004

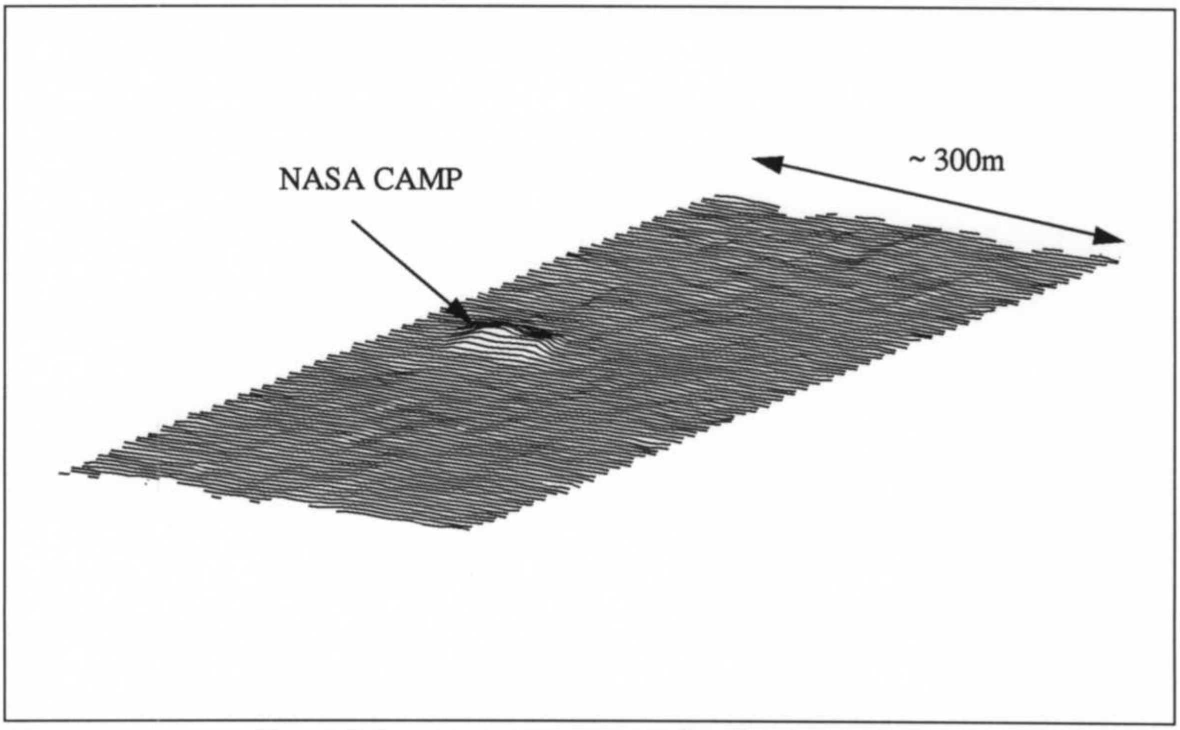

Figure 5. Perspective view of NASA Camp subarea

3.4. Details of Reduction of Latitude and Longitude

The following is a detailed description of latitude and longitude reduction process.

1) 1991 North and South Line

Starting Point: NCP (91)
Position: 69-51-37.24807, 313-0-10.530149
Forward Azimuth from NCP to N10: 27-11-42.05382
Forward Azimuth from NCP to S10: 207-11-42.05382
Average Height above ellipsoid: (S10+N10)/2 = (1933.773+1991.370)/2=1962.572 m

2) 1992 NCP to N5 Line

Starting Point: NCP (92)
Position: 69-51-36.25366, 313-0-3.96968
Forward Azimuth from NCP to N5: 27-12-42.43884
Average Height above ellipsoid: (NCP+N5)/2=(1991.228+2001.604)/2=1996.416 m

3) 1992 N5 to N9 Line

Starting Point: N5 (92)
Position: 69-54-2.51030, 313-3-42.69045
Forward Azimuth from N5 to N9: 27-15-48.21648
Average Height above ellipsoid: (N5+N9)/2=(2001.772+1973.010)/2=1987.391 m

4) 1992 N9 to N10 Line

Starting Point: N9 (92)
Position: 69-55-53.90726, 313-6-29.87614
Forward Azimuth from N9 to N10: 27-10-11.47990
Average Height above ellipsoid: (N9+N10)/2=(1972.842+1989.550)/2=1981.196 m

5) 1992 N10 to N17 Line

Starting Point: N10 (92)
Position: 69-56-23.30293, 313-7-13.82986
Forward Azimuth from N10 to N17: 27-21-45.01847
Average Height above ellipsoid: (N10+N17)/2=(1989.550+2055.394)/2=2022.472 m

6) 1992 N17 to N23 Line

Starting Point: N17 (92)
Position: 69-59-41.29670, 313-12-13.21416
Forward Azimuth from N17 to N23: 27-26-24.54168
Average Height above ellipsoid: (N17+N23)/2=(2055.394+2089.011)/2=2072.203 m

7) 1992 N23 to N32 Line

Starting Point: N23 (92)
Position: 70-2-37.41743, 313-16-41.02907
Forward Azimuth from N23 to N32: 27-27-33.94450
Average Height above ellipsoid: (N23+N32)/2=(2089.011+2113.350)/2=2101.181 m

8) 1992 NC10 to NC1 Line

Starting Point: NC10 (92)
Position: 69-58-22.61644, 313-19-31.64494
Forward Azimuth from NC10 to NC1: 297-42-23.40966
Average Height above ellipsoid: (NC10+NC1)/2=(2081.369+2036.256)/2=2058.813 m

9) 1992 N5 to Lake Line

Starting Point: N5 (92)
Position: 69-54-2.51030, 313-3-42.69045
Forward Azimuth from N5 to Lake: 301-37-50.04044
Average Height above ellipsoid: (N5+Lake)/2=(2001.604+1972.997)/2=1987.301 m

10) 1992 Lake to CP Line
Starting Point: Lake(92)
Position: 69-56-18.02381, 312-53-0.30083
Forward Azimuth from Lake to CP: 179-16-47.26735
Average Height above ellipsoid: (Lake+CP)/2=(1972.997+1942.846)/2=1957.922 m

11) 1992 WCR to CP Line

Starting Point: WCR(92)
Position: 69-52-43.79565,312-48-46.59502
Forward Azimuth from WCR to CP: 116-31-55.91485
Average Height above ellipsoid: (WCR+CP)/2=(1943.664+1942.846)/2=1943.255 m

12) 1992 CP to SC15 Line

Starting Point: CP(92)
Position: 69-51-58.47573,312-53-9.77194
Forward Azimuth from CP to SC15: 115-53-15.82162
Average Height above ellipsoid: (CP+SC15)/2=(1942.846+2021.786)/2=1982.316 m

4. GPS measurements and leveling

The reference for surface GPS measurement is the WGS84 ellipsoid. The reference for leveling is the geoid. The difference between these two references is shown in Figure 5. As shown

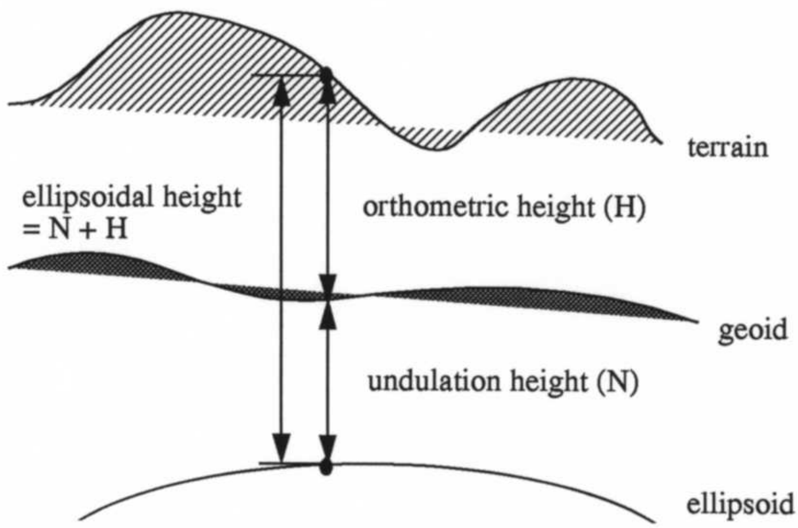

Figure 5. Two different references: ellipsoid and geoid

in the figure, the ellipsoidal height and the orthometric height differ by the undulation height. As mentioned earlier, one of the surface GPS points is used for the starting reference point and the other surface GPS points are tied together with surface leveling. In 1991 and 1992, NCP(91) and NCP(92) are used as the starting reference points, respectively. The height differences between surface GPS and leveling are listed in Table 7. The height difference between surface GPS and leveling along the leveling line is shown in Figure 6. Part of this elevation difference is due to random instrumental errors and part is likely due to geoid undulation, as can be seen in Figure 6.

To check the accuracy of leveling, closure of leveling are checked in Crawford Point. By accounting for snow accumulation and ablation during leveling, the accuracy of leveling is about 5.2cm over a 30 km leveling line.

Table 7: Height Difference Between GPS and Leveling

Station	height of leveling (m)	GPS height (m)	GPS - leveling (m)
NCP (91)-North	1991.503	1991.305	-0.198
NCP(91)-South	1991.613	1991.415	-0.198
N10 (91)	1991.370	1991.370	0.000
S10	1933.772	1933.175	-0.597
S5	1929.729	1929.358	-0.371
SC15	2021.786	2021.542	-0.244
NCP	1991.228	1991.395	0.167
CAMP	2006.348	2006.600	0.252
CP	1942.846	1942.391	-0.455
WCR	1943.664	1942.980	-0.684
N5	2001.604	2001.430	-0.174
LAKE	1972.997	1972.501	-0.496
N9	1972.842	1972.801	-0.041
N10	1989.550	1989.550	0.000
N17	2055.394	2055.549	0.155
NC1	2036.256	2036.474	0.218
N23	2089.011	2089.616	0.605
N32	2113.350	2114.041	0.691

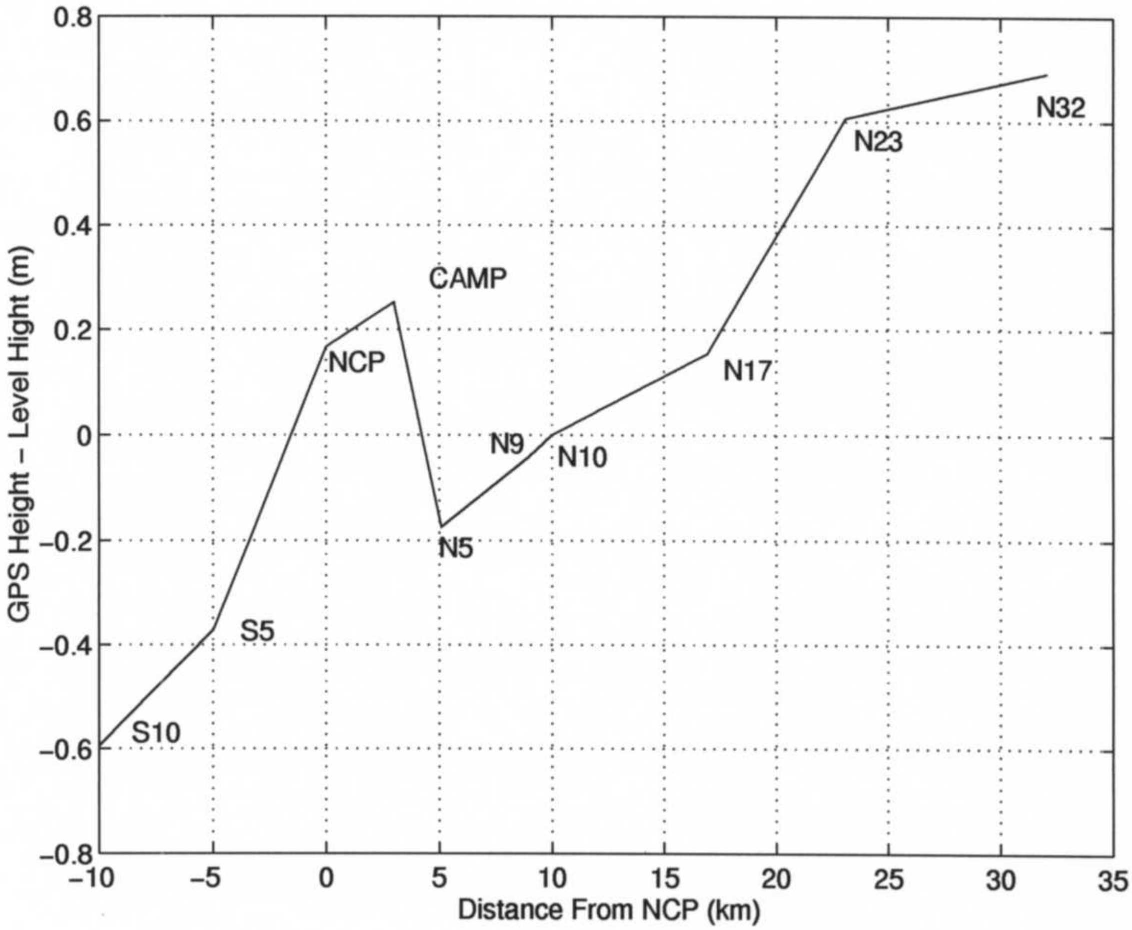

Figure 6. Height Difference Between GPS and leveling along the level line (1992)

5. Surface Velocity Measurements

By using latitude and longitude points measured in 1991 and 1992, we calculated the displacement of a point between 1991 and 1992. By using the time gap at the same point, we calculated the surface velocity. Table 8 is the results of this calculation. Figure 7 shows the velocity magnitude and direction for N32 to S10.

Table 8: Surface Velocity Magnitude and Direction

ID	92	91	interval (days)	azimuth direction (91 to 92)	distance(m)	speed (cm /day)
N32	June-9-92	Aug-27-91	305	232-30-44.32	80.89	26.52
N31	June-9-92	Aug-27-91	305	232-34-45.94	80.90	26.52
N30	June-9-92	Aug-27-91	305	233-0-41.67	79.85	26.18
N29	June-9-92	Aug-27-91	305	233-55-19.33	77.46	25.40
N28	June-9-92	Aug-27-91	305	234-46-41.61	75.42	24.73
N27	June-9-92	Aug-27-91	305	235-3-3.00	74.93	24.57
N26	June-9-92	Aug-27-91	305	235-21-53.56	74.36	24.38
N25	June-9-92	Aug-27-91	305	235-22-22.89	74.48	24.42
N24	June-9-92	Aug-27-91	305	234-57-16.58	75.76	24.84
N23	June-9-92	Aug-27-91	305	234-47-46.61	76.33	25.03
N22	June-8-92	Aug-27-91	304	236-1-35.92	75.71	24.90
N21	June-8-92	Aug-27-91	304	236-1-9.28	77.52	25.50
N20	June-8-92	Aug-25-91	306	236-48-0.57	77.66	25.38
N19	June-8-92	Aug-25-91	306	237-41-19.27	77.43	25.30
N18	June-8-92	Aug-25-91	306	239-22-30.62	75.65	24.72
N17	June-8-92	Aug-25-91	306	239-22-19.71	77.65	25.38
N16	June-8-92	Aug-25-91	306	241-8-33.96	75.74	24.75
N15	June-8-92	Aug-25-91	306	240-21-38.33	79.00	25.82
N14	June-8-92	Aug-25-91	306	240-30-58.23	80.71	26.38
N13	June-8-92	Aug-25-91	306	240-3-24.52	83.27	27.21
N12	June-8-92	Aug-25-91	306	240-46-23.29	83.49	27.28

Table 8: Surface Velocity Magnitude and Direction

ID	92	91	interval (days)	azimuth direction (91 to 92)	distance(m)	speed (cm /day)
N11	June-8-92	Aug-25-91	306	241-48-27.95	82.83	27.07
N10	June-7-92	Aug-25-91	305	243-51-19.28	80.64	26.44
N9	June-7-92	Aug-25-91	305	245-12-53.24	74.52	24.43
N8	June-7-92	Aug-25-91	305	245-53-38.94	73.62	24.14
N7	June-7-92	Aug-24-91	306	247-23-1.00	71.57	23.39
N6	June-7-92	Aug-24-91	306	249-34-12.18	68.91	22.52
N5	June-7-92	Aug-24-91	306	250-31-0.92	67.97	22.21
N4	June-6-92	Aug-24-91	306	249-28-1.21	69.82	22.82
N3	June-5-92	Aug-24-91	305	249-0-4.04	70.94	23.26
N2	June-5-92	Aug-24-91	305	247-24-17.46	73.71	24.17
N1	June-5-92	Aug-24-91	305	246-44-57.59	75.24	24.67
CP	June-5-91	Aug-24-91	305	246-15-19.89	76.53	25.09
S1	June-5-92	Aug-28-91	301	246-15-54.77	76.82	25.52
S2	June-5-92	Aug-28-91	301	247-22-30.39	75.33	25.03
S3	June-5-92	Aug-28-91	301	248-25-51.59	74.03	24.59
S4	June-5-92	Aug-28-91	301	249-31-49.71	72.75	24.17
S5	June-5-92	Aug-28-91	301	251-23-33.89	70.51	23.43
S6	June-6-92	Aug-28-91	302	252-57-0.39	72.04	23.85
S7	June-6-92	Aug-28-91	302	254-57-26.21	72.13	23.88
S8	June-6-92	Aug-28-91	302	256-34-25.17	73.42	24.31
S9	June-6-92	Aug-28-91	302	258-13-13.60	74.76	24.76
S10	June-6-92	Aug-28-91	302	259-1-17.47	76.41	25.30

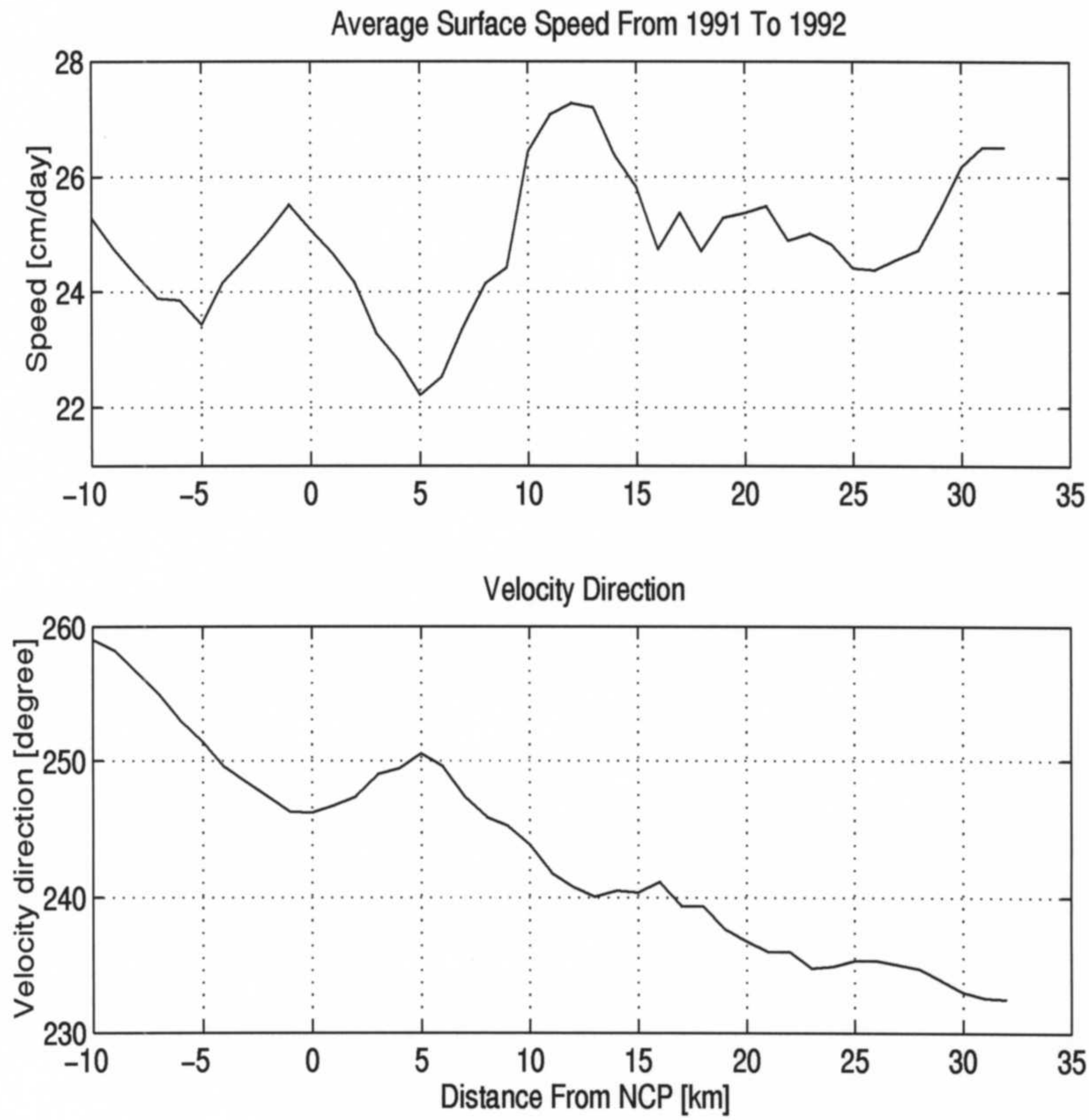

Figure 7. Velocity and direction of velocity: from S10 to N32

6. Surface Accumulation Measurements

The heights of aluminum and bamboo poles were measured along the level line. Table 9 and 10 show the results. The height of aluminum and bamboo poles is defined as (see, Figure 8):

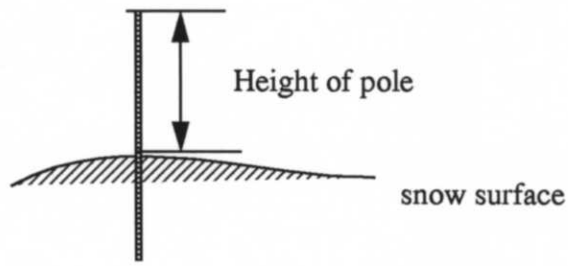

Figure 8. The height of aluminum and bamboo pole

Table 9: The height of Aluminum and Bamboo Pole (1991)

Date/Station	Aluminum (cm)*	Bamboo (cm)	Station	Aluminum (cm)	Bamboo (cm)
8-24-91					
NCP	75+AL†	n/a	N1	93+AL	240
N2	84+AL	293	N3	80+AL	288
N4	69+AL	290	N5	89+AL	286
N6	91+AL	277	N7	112.5+AL	303
8-25-91					
N8	102+AL	270	N9	116+AL	283
N10	93+AL	298	N11	92+AL	256
N12	103+AL	263	N13	95+AL	267
N14	76+AL	273	N15	94+AL	287
N16	103+AL	294	N17	104+AL	297
N18	104+AL	262	N19	97+AL	297
N20	100+AL	256			
8-27-91					
N21	95+AL	257	N22	98+AL	285

Table 9: The height of Aluminum and Bamboo Pole (1991)

Date/Station	Aluminum (cm)*	Bamboo (cm)	Station	Aluminum (cm)	Bamboo (cm)
N23	105+AL	295	N24	95+AL	294
N25	97+AL	293	N26	117+AL	265
N27	105+AL	265	N28	86+AL	285
N29	106+AL	286	N30	110+AL	293
N31	80+AL	263	N32	88+AL	276
8-28-91					
S1	104+AL	258	S2	128+AL	255
S3	112+AL	265	S4	122+AL	301
S5	112+AL	290	S6	124+AL	270
S7	112+AL	280	S8	101+AL	294
S9	106+AL	285	S10	108+AL	291

*. The height of aluminum pole is 183 cm

†. The height of aluminum pole is 183 cm.

Table 10: The height of Aluminum and Bamboo Pole (1992)

Date/Station	Aluminum (cm)	Bamboo (cm)	Station	Aluminum (cm)	Bamboo (cm)
June-5-92					
N3	156	187	N2	163	191
N1	171.5	137	NCP	151	n/a
S1	202	178	S2	201	148
S3	187	158	S4	195	197
S5	182	176			
June-6-92					
S6	196	156	S7	175	160
S8	185	194.5	S9	182	177
S10	176.5	175	WCR	90+AL=273	n/a

Table 10: The height of Aluminum and Bamboo Pole (1992)

Date/Station	Aluminum (cm)	Bamboo (cm)	Station	Aluminum (cm)	Bamboo (cm)
CP	101+AL=284	n/a	SC5	324	n/a
June-7-92					
SC6	84+AL=267	n/a	SC7	105+AL=288	316
SC8	99+AL=282	291	SC9	103	284
SC10	105.5	303	S1	201	n/a
N3	158	n/a	N4	138	184
N5	170	179	N6	153	158
N7	179	185	N8	164	148
N9	183	163	N10	175	n/a
June-8-92					
N10	174.5	n/a	N11	189	166
N12	199	176	N13	182	169
N14	157	168	N15	180	185
N16	183.5	190	N17	177.5	184
N18	173	147	N19	166	184
N20	194	163	N21	181	155
N22	201	202	N23	187	190
June-9-92					
N24	184	197	N25	183	197
N26	198	164	N27	196.5	172
N28	176	191	N29	204	200
N30	212	214	N31	168	167
N32	159	164			
June-10-92					
NC10	112	315	NC9	124.5	312
NC8	120	287	NC7	124	312

Table 10: The height of Aluminum and Bamboo Pole (1992)

Date/Station	Aluminum (cm)	Bamboo (cm)	Station	Aluminum (cm)	Bamboo (cm)
NC6	116	332	N17	175	186
NC5	123.5	310	NC4	107.5	320
NC3	115	278	NC2	121	283
NC1	103	293			
June-13-92					
SC10	104	302	SC11	105	313
SC12	102	314	SC13	105	306
SC14	96	310	SC15	94	317
June-16-92					
N9	179	315	N3	337	335
June-17-92					
N5	172	n/a	PE1	95	304
PE2	103	293	PE3	113	302
PE4	122	308	PE5	119.5	307
PE6	98.4	304	PE7	101.5	322.7
PE8-Lake	102	267	PN1	99.5	290
PN2	117	321	PN3	92	291
PN4	112	295	PN5	102	282
PN6	113	309	PN7	119	309
CF-CR	275 (above board)	n/a			