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DISTANCE MEASUREMENTS IN 1977 IN THE KRAFLA-MÝVATN AREA AND OBSERVED GROUND MOVEMENTS

by

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ABSTRACT

A network of bench marks for distance measurements was established along the Krafla fissure swarm from Leirhnjúkur in the south towards the latitude of Hrútafjöll in the north. This network consists of 43 bench marks and covers an area roughly 12 km long in north-south direction and 5 km wide in east-west direction. Distances between adjacent bench marks are usually between one and two kilometers. Measurements were performed four times in 1977 on large or small portions of this network, first in late February to early March. Horizontal ground movement during the April 1977 and September 1977 subsidence events of the Krafla caldera were observed to amount to 70 to 100 cm in east-west expansion for each event and vertical movements of similar magnitude were observed. Another network of bench marks was established and measured in July and August, 1977, south of Krafla covering an area of roughly 35 km in north-south direction and 15 km in east-west direction consisting of 12 bench marks with distances between bench marks of 3 to 14 km. The northern part of this network was remeasured after the September, 1977, subsidence event and east-west tensional movement of 75 to 105 cm was observed. A few additional distance measurements were made in the Námafjall area.

THE GJÁSTYKKI NETWORK

In late February, 1977, a network of bench marks was constructed in the southern part of Gjástykki and the northern part of the Krafla caldera, consisting of 43 bench marks identified as A001 through A043 forming 10 lines crossing the Krafla fissure swarm (Fig. 1). The distance between the adjacent bench marks was kept within 2 kilometers to allow distance measurements with "Distomat" which was available for use in this area. On February 26 to March 1, 1977, a total of 39 bench mark distances were measured, thereof 36 in both directions, covering bench marks A001 through A036 and A038. Vertical and horizontal angles were observed with T-16 or T-2 theodolites. The distance measurements did not form a net of triangles, so coordinates of bench marks were not obtained with the desired accuracy.

On July 19 to 21, 1977, geodimeter measurements were made on 14 distances in the southern part of the Gjástykki network and four of these distances were measured again on August 18, 1977.

On October 23 to 26, 1977, 8 distances were measured in the southern part of the network and 16 more distances were measured on November 25 to 29, 1977, in the central part of the network, so a total of 24 bench mark distances were measured in October and November, 1977.

Thus 4 bench mark distances in the Gjástykki network were measured four times in 1977, 10 distances were measured three times, another 10 distances were measured two times and 15 distances were measured only once in 1977.

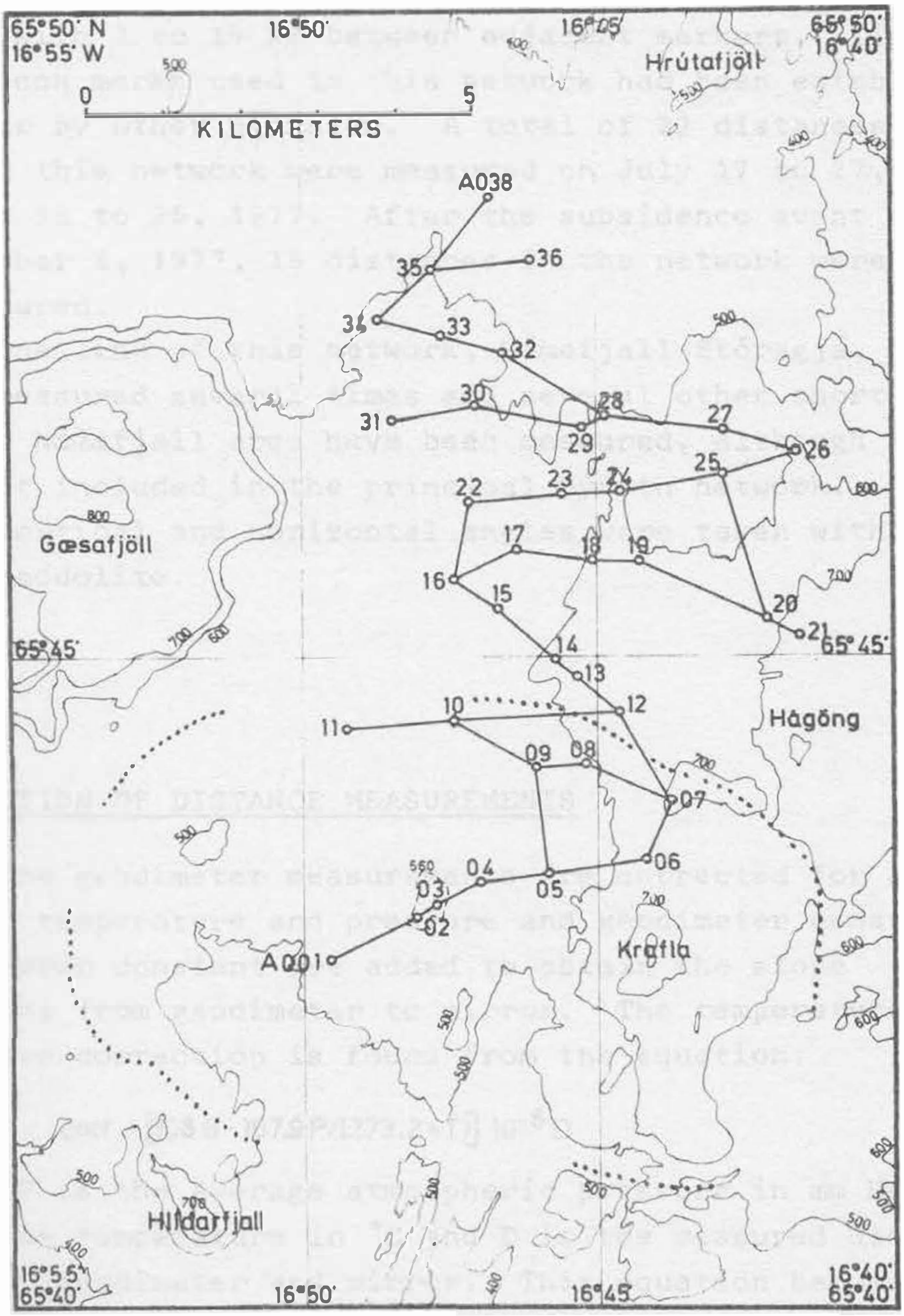


Fig. 1. The Gjástykki geodimeter network of 1977.

THE MÝVATN NETWORK

In July and August 1977 a geodimeter network in the Mývatn area was established. This consists of 12 bench marks with 3 to 14 km between adjacent markers. Eight of the bench marks used in this network had been established earlier by other agencies. A total of 22 distances within this network were measured on July 17 to 27, and August 15 to 25, 1977. After the subsidence event on September 8, 1977, 15 distances in the network were remeasured.

One line of this network, Námafjall-Stóragjá, has been measured several times and several other short lines in the Námafjall area have been measured, although they are not included in the principal Mývatn network.

Vertical and horizontal angles were taken with the T-2 theodolite.

CORRECTION OF DISTANCE MEASUREMENTS

The geodimeter measurements are corrected for atmospheric temperature and pressure and geodimeter constant and mirror constant are added to obtain the slope distance from geodimeter to mirror. The temperature and pressure correction is found from the equation:

$$\text{corr.} = [308.6 - 107.9\,P/(273.2 + T)]\,10^{-6}\,D \qquad (1)$$

where P is the average atmospheric pressure in mm Hg, T is the temperature in °C and D is the measured distance between geodimeter and mirror. This equation becomes:

$$\text{corr.} = [308.6 - 80.9\,P/(273.2 + T)]\,10^{-6}\,D \qquad (2)$$

if the pressure is in millibars and temperature in °C.

Both pressure and temperature are read at the geodimeter and the mirror station and the average of these two readings is used to obtain the temperature and pressure correction. It is obvious that this method may introduce error in the distance. The temperature is read near the ground at both ends of the measured line while segments of the line are frequently high above the ground, where temperature conditions may be significantly different from near-ground conditions. The error due to different pressure near ground and along the line of measurement is, however, not significant.

The error in length due to 1°C error in the average temperature along the line of measurement amounts to roughly $0.9 \times 10^{-6}D$ to $1.2 \times 10^{-6}D$ under the temperature and pressure conditions which will be encountered in Iceland. Greatest errors will be introduced if temperature is low while pressure is high.

The error in length due to 1 mm Hg error in average pressure along the line of measurement is $0.37 \times 10^{-6}D$ to $0.41 \times 10^{-6}D$ under icelandic conditions, increasing with decreasing temperature.

The geodimeter constant is given by the manufacturer as -0.125 m for the instrument of the Nordic Volcanological Institute and the mirror constant for the mirrors and mirror holders used by the institute is given as 0.000 m by the manufacturer. If other geodimeters or mirrors are used, the corresponding geodimeter and mirror corrections have to be applied.

The calculated distance, after temperature-, pressure-, geodimeter- and mirror-corrections have been applied is considered as the true distance between the geodimeter and the mirror, or rather the true distance between two points, one vertically above the geodimeter bench mark at height equal that of the optical axis of the geodimeter, another vertically above the mirror bench mark at height equal the height of the center of gravity of the mirrors.

REDUCTION OF DISTANCES TO BENCH MARKS

The reduction of geodimeter-mirror distance to bench mark-bench mark distance requires knowledge of geodimeter height, mirror height and the height angle (vertical angle) from geodimeter bench mark to mirror bench mark. The height of geodimeter and mirror is obtained by measuring the vertical distance from the bench mark to the plate of corresponding tripod and add the constant height of geodimeter or mirrors above the tripod plate. The mirror height above the tripod plate may vary, depending on number and position of mirrors in the mirror holder.

The vertical angle from geodimeter bench mark to the mirror bench mark is observed with a theodolite. As both theodolite and the "target" are normally above the bench marks, the vertical angle has to be reduced to the bench marks (Fig. 2).

The measured geodimeter distances are short, compared to the radius of curvature of the earth's surface, so the curvature can be omitted in reduction of the vertical angle. As the reduced vertical angle is used for obtaining elevation differences of bench marks, and horizontal (sea level) distances between bench marks, the refraction of light is included in the reduction of the vertical angle. The equation used in this reduction is:

$$\varphi = \varphi^{*} + (H_t - H_i)\sin\varphi^{*}/M + M/70\,000\,000 \qquad (3)$$

where the last item is the refraction effect (see Appendix II). The notation in equation (3) are

- φ vertical angle between bench marks in radians,
- φ^{*} observed vertical angle ($\pi/2$ = horizontal, 0 to zenith),
- H_i theodolite height at geodimeter site in meters,
- H_t target height at mirror site in meters,
- M measured distance, geodimeter-mirror in meters.

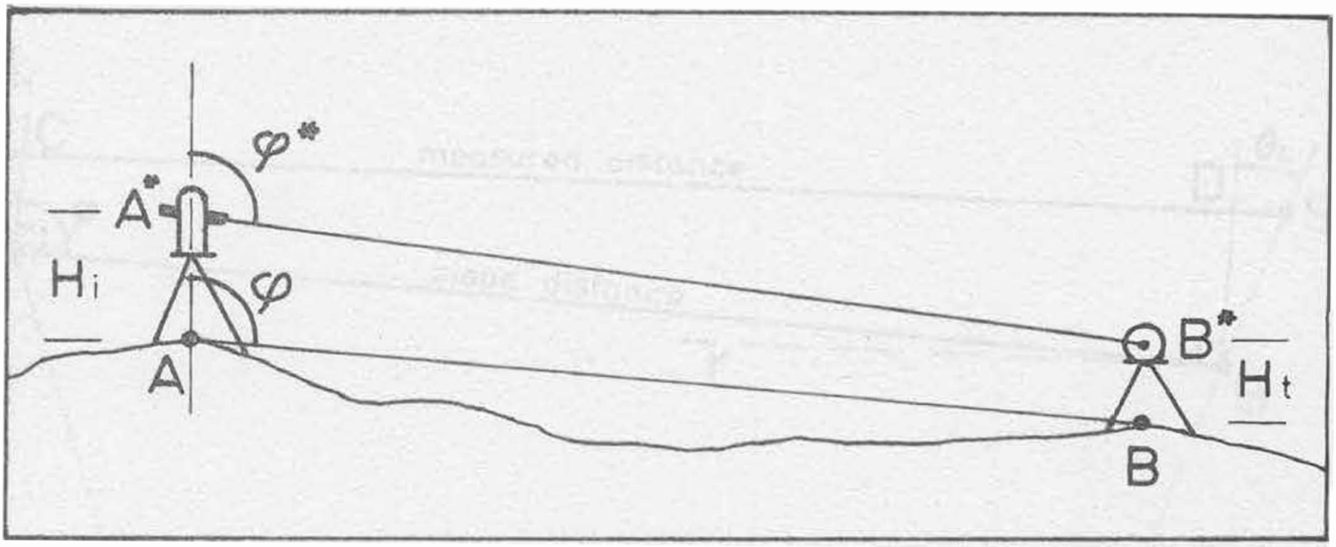


Fig. 2. Reduction of measured vertical angle φ^* to vertical angle between bench marks φ . A is theodolite station, B is target station. H_i is height of theodolite above bench mark, H_t is height of target above bench mark.

The slope distance between bench marks (A and B on Fig. 2) can now be calculated from the measured distance (M), geodimeter height (Hg), mirror height (H_s) and vertical angle (φ) together with the radius of curvature of the earth surface.

From Fig. 3 we see that the measured distance is:

$$M = \overline{GS} = \overline{GC} + \overline{CD} + \overline{DS} \qquad (4)$$

and the bench mark distance is

$$L = \overline{AB} = \overline{CD}\cos\gamma \qquad (5)$$

The distances $\overline{GC}$ and $\overline{DS}$ are:

$$\overline{GC} = H_g \sin\theta_1 \qquad \overline{DS} = H_s \sin\theta_2 \qquad (6)$$

where

$$\theta_1 = \varphi - \pi/2 \; ; \qquad \theta_2 = \pi/2 - \varphi + \alpha \qquad (7)$$

and α is the central angle, approximately $\frac{M}{R}$ radians. R is the radius of curvature of the earth´s surface, approximately 6.388 x 10^6 meter in Iceland.

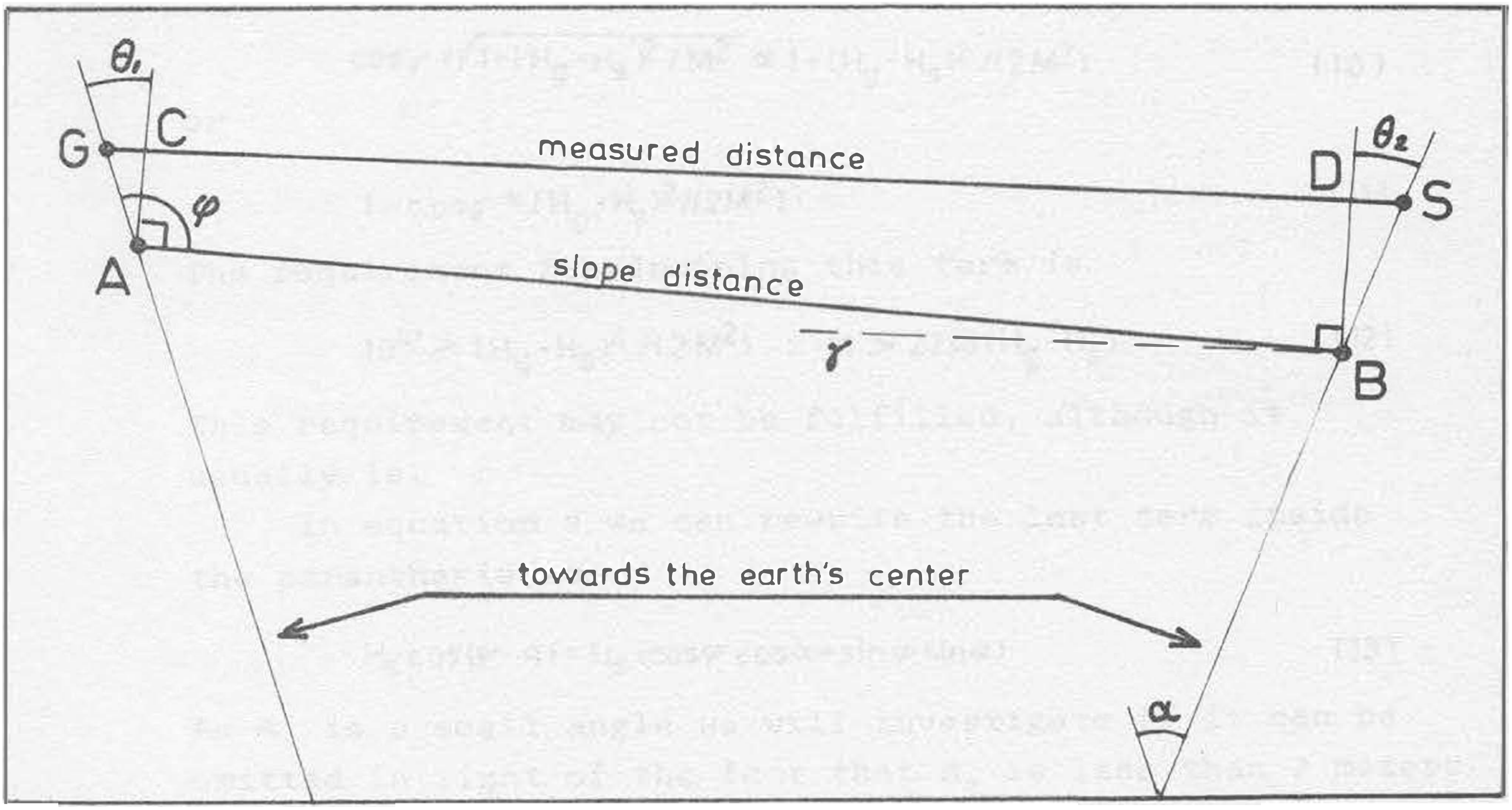


Fig. 3. Reduction of measured distances to slope distances between bench marks. A and B are bench marks, G is the geodimeter and S is the mirror. φ is the vertical angle between bench marks. The angle α is between the vertical at A and B. γ is the angle between the line AB and the line GS.

From (6) and (7) we get:

$$GC + DS = H_s \cos(\varphi - \alpha) - H_g \cos\varphi \tag{8}$$

Therefore from (4), (5) and (8)

$$L = [M + H_g \cos\varphi - H_s \cos(\varphi - \alpha)] \cos\gamma \tag{9}$$

As the accuracy of measurement is less than 10^{-6} we need not include in the reduction of data any terms which are much smaller than expected errors.

As $\cos\gamma$ is a multiplication factor, we can omit it if its value is less than 10^{-7} from unity, otherwise it should be included. The angle γ is approximately equal to $(H_G - H_s)/M$ radians, so we have approximately

$$\cos\gamma = \sqrt{1-(H_g-H_s)^2/M^2} \simeq 1-(H_g-H_s)^2/(2M^2) \qquad (10)$$

or

$$1-\cos\gamma \simeq (H_g-H_s)^2/(2M^2) \qquad (11)$$

The requirement for dropping this term is

$$10^{-7} > (H_g-H_s)^2/(2M^2) \qquad M > 2236(H_g-H_s) \qquad (12)$$

This requirement may not be fulfilled, although it usually is.

In equation 9 we can rewrite the last term inside the paranthesis as:

$$H_s\cos(\varphi-\alpha) = H_s(\cos\varphi\cos\alpha+\sin\varphi\sin\alpha) \qquad (13)$$

As α is a small angle we will investigate if it can be omitted in light of the fact that H_s is less than 2 meters and introduction of errors of 0.1 millimeter is insignificant.

Considering distances less than 20 km, we have

$$\sin\alpha \simeq \alpha < 0.00313 \qquad (14)$$

The vertical angle φ deviates less than 5 grad from the horizont in all normal cases, except for very short distances between geodimeter and mirror. Therefore we can set

$$\sin\varphi\sin\alpha < 0.003 \qquad (15)$$

omission of which may cause orror of about 5 mm in reduced length. Therefore, this term should not be omitted.

Omission of $\cos\alpha$ in first term inside the paranthesis in (13) will introduce errors of less than 0.01 mm and is therefore permissible.

Therefore we will rewrite equation 9 in the following form:

$$L = M+(H_g-H_s)\cos\varphi - H_sM\sin\varphi/R-(H_g-H_s)^2/(2M) \qquad (16)$$

CALCULATION OF ELEVATION DIFFERENCES

The elevation difference between two bench marks is calculated from the vertical angle φ the slope distance L between the bench marks A and B and the radius of curvature of the earth surface (Fig. 4). The point B´ is at the same elevation as A, so the distance B´B is equal the elevation difference H of the stations A and B.

In the triangle A B´ B, the angles are in radians:

$$\psi = \varphi - \alpha/2 - \pi/2$$
$$\gamma = \pi/2 - \alpha/2$$
$$\beta = \pi/2 - \varphi + \alpha$$

The sine rule gives:

$$\sin\gamma / L = \sin\psi / (-H) \quad (17)$$

where L is the corrected slope distance between the bench marks.
We rewrite

$$\sin\gamma = \sin(\pi - \alpha/2) = \cos(\alpha/2) \quad (18)$$

$$\sin\psi = \sin(\varphi - \alpha/2 - \pi/2) = -\cos\varphi\cos(\alpha/2) - \sin\varphi\sin(\alpha/2) \quad (19)$$

and equation (17) may be written:

$$H = L\cos\varphi + L\sin\varphi\tan(\alpha/2) \quad (20)$$

As the angle $\alpha/2$ is generally less than 0.002 radians, tan $\alpha/2$ may be written as $\frac{L\sin\varphi}{2R}$ without introducing any significant error. Thus equation (20) may be written as:

$$H = L\cos\varphi + L^2/(2R) - L^2\cos^2\varphi/(2R) \quad (21)$$

The last term of (21) may be written

$$L^2\cos^2\varphi/(2R) = H^2/(2R) \quad (22)$$

and if H is less than 200 meter, this term is less than 3.1 mm and thus not significant as the accuracy in the elevation difference is normally roughly 3 cm. However, if the elevation difference is greater than 500 m this term becomes significant and, therefore, equation (21) should be used unabridged when elevation differences of bench marks are calculated.

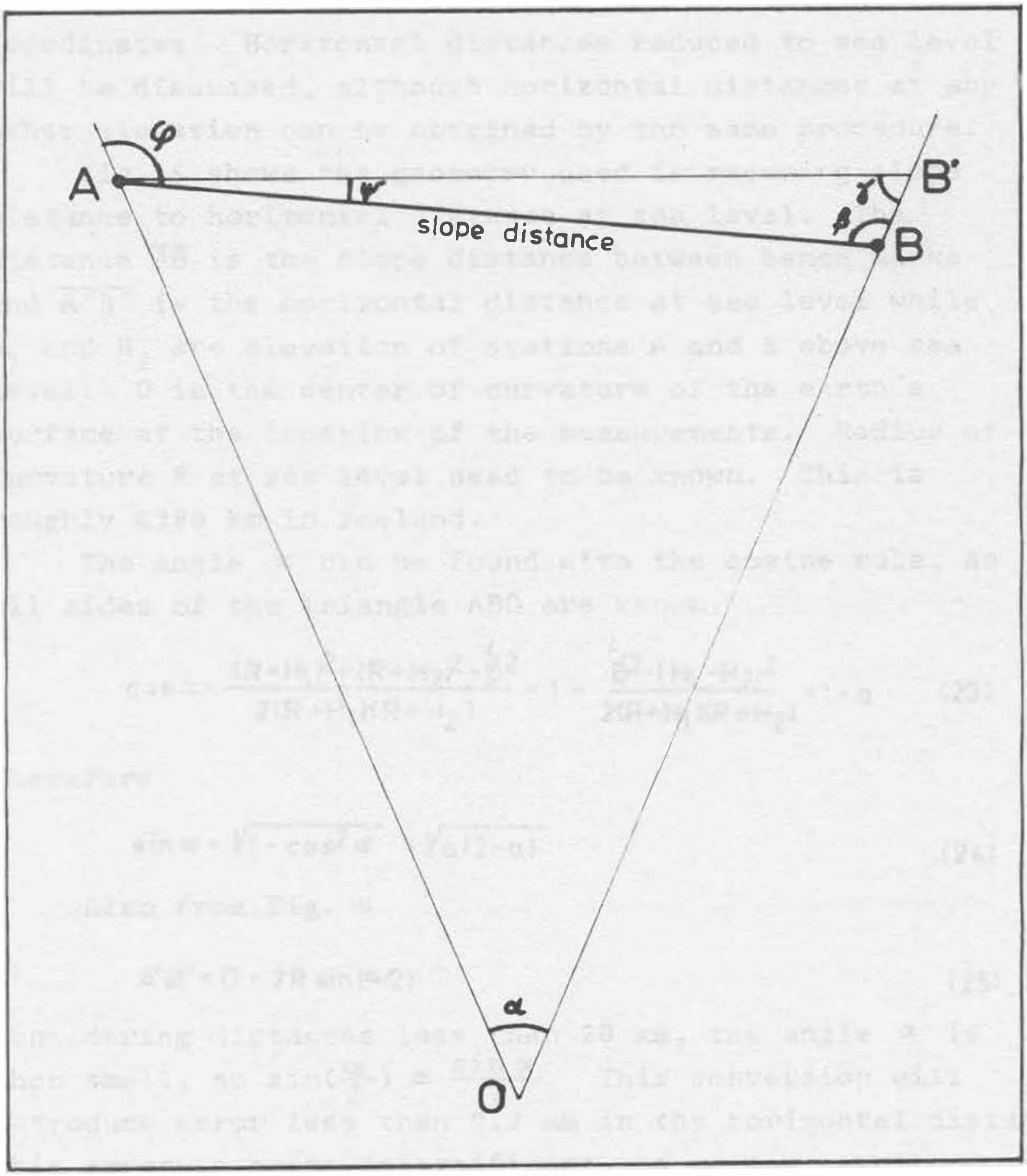


Fig. 4. Elevation difference of two bench marks. A and B are bench marks, B´ is an imaginary point vertically above B at the elevation of A, O is the center of curvature of the earth´s surface. BB´ is equal the elevation difference of the stations A and B. φ is the vertical angle from A to B.

CALCULATION OF HORIZONTAL DISTANCE BETWEEN BENCH MARKS

It is convenient to use horizontal distances rather than slope distances in determination of station coordinates. Horizontal distances reduced to sea level will be discussed, although horizontal distances at any other elevation can be obtained by the same procedure.

Fig. 5 shows the geometry used in reducing slope distance to horizontal distance at sea level. The distance AB is the slope distance between bench marks and A´B´ is the horizontal distance at sea level while H_1 and H_2 are elevation of stations A and B above sea level. O is the center of curvature of the earth´s surface at the location of the measurements. Radius of curvature R at sea level need to be known. This is roughly 6388 km in Iceland.

The angle α can be found with the cosine rule, as all sides of the triangle ABO are known.

$$\cos\alpha = \frac{(R+H_1)^2+(R+H_2)^2-L^2}{2(R+H_1)(R+H_2)} = 1 - \frac{L^2-(H_1-H_2)^2}{2(R+H_1)(R+H_2)} = 1 - a \qquad (23)$$

Therefore

$$\sin\alpha = \sqrt{1-\cos^2\alpha} = \sqrt{a(2-a)} \qquad (24)$$

Also from Fig. 4

$$A'B' = D = 2R\sin(\alpha/2) \qquad (25)$$

considering distances less than 20 km, the angle α is then small, so $\sin(\frac{\alpha}{2}) \simeq \frac{\sin\alpha}{2}$. This conversion will introduce error less than 0.2 mm in the horizontal distance. This error is quite insignificant, so we may rewrite equation (25) as:

$$D = R\sin\alpha = R\sqrt{a(2-a)} \qquad (26)$$

where a is as given in (23)

$$a = \frac{L^2-(H_1-H_2)^2}{2(R+H_1)(R+H_2)} \qquad (27)$$

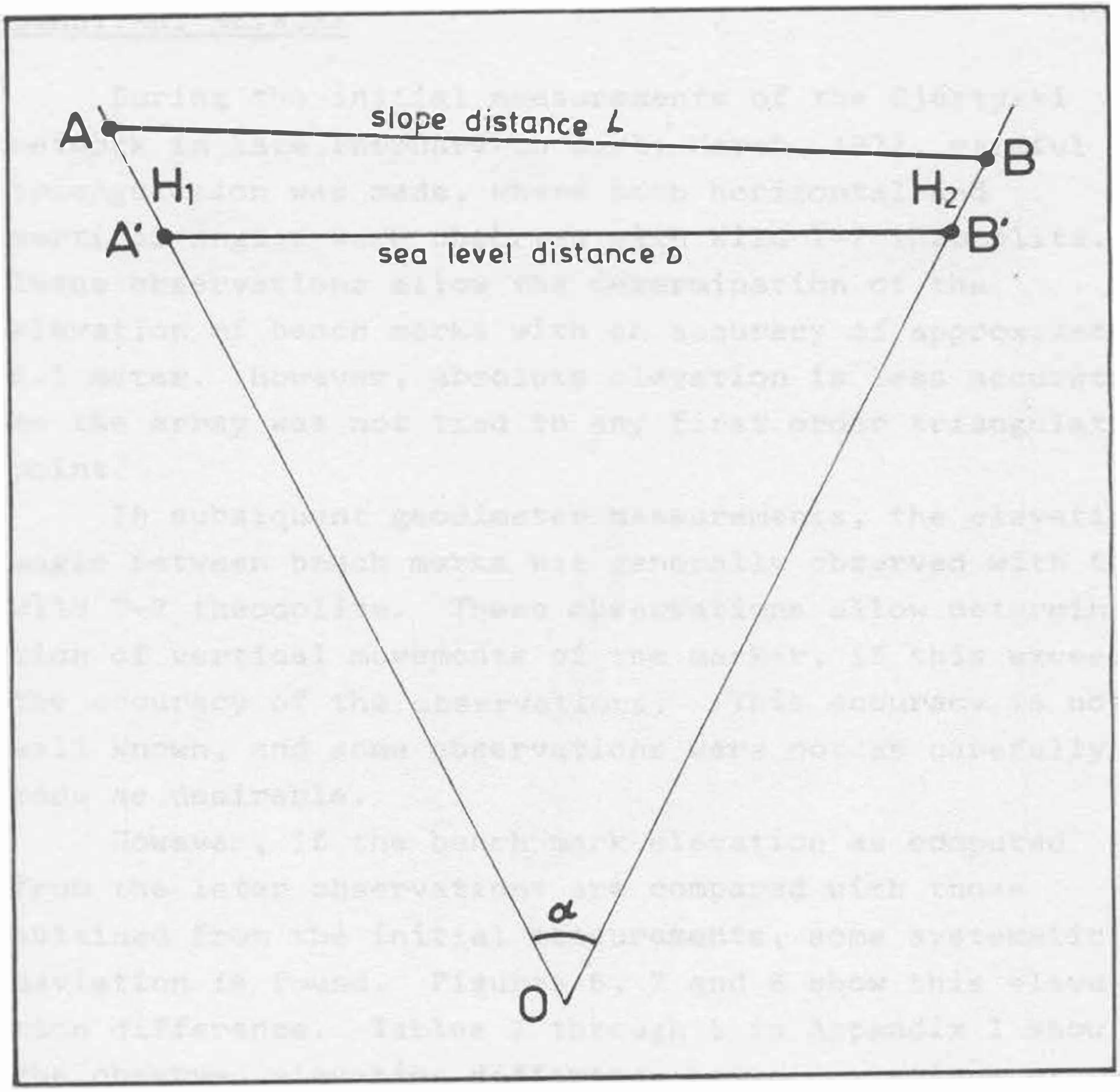


Fig. 5. Reduction of slope distance to sea-level horizontal distance. A and B are bench marks, A´ and B´ are imaginary points at sea-level vertically below A and B. On the center of curvature of the earth´s surface. H_1 and H_2 are elevations of A and B.

ELEVATION AND CHANGE IN ELEVATION OF BENCH MARKS IN THE GJÁSTYKKI NETWORK

During the initial measurements of the Gjástykki network in late February to early March, 1977, careful triangulation was made, where both horizontal and vertical angles were observed with Wild T-2 theodolite. These observations allow the determination of the elevation of bench marks with an accuracy of approximately 0.1 meter. However, absolute elevation is less accurate, as the array was not tied to any first order triangulation point.

In subsiquent geodimeter measurements, the elevation angle between bench marks was generally observed with the Wild T-2 theodolite. These observations allow determination of vertical movements of the marker, if this exceeds the accuracy of the observations. This accuracy is not well known, and some observations were not as carefully made as desirable.

However, if the bench mark elevation as computed from the later observations are compared with those obtained from the initial measurements, some systematic deviation is found. Figures 6, 7 and 8 show this elevation difference. Tables 1 through 5 in Appendix I show the observed elevation difference between stations at the time of the observations. The station elevation is taken as 542.00 m at station A001, which agrees with that given for this point on the U.S. Army Map Service map in 1:50.000 of 1949 (Table 10).

In obtaining the change in elevation of the bench marks, some assumptions are made. The stations A009, A010 and A011 were not tied to the rest of the array during the July 1977 observation, but they were tied internally . As station A009 had apparently been uplifted 8 cm relative to station A007 from the initial measurement to the last measurement in 1977, it is assumed that 4 cm of this relative uplift occurred before the July observation.

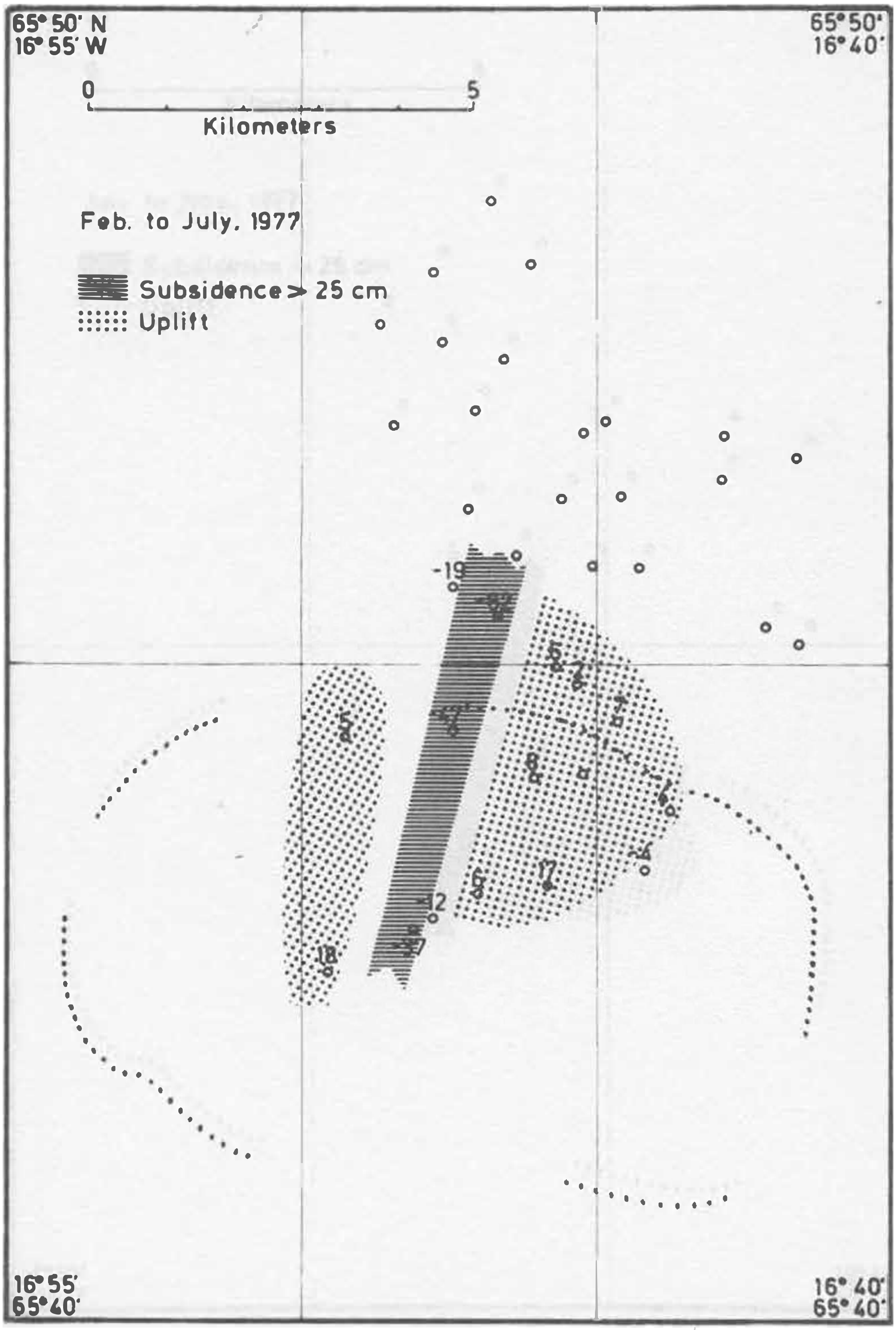


Fig. 6 Observed elevation changes of bench marks in the Gjástykki network between measurements in February and July, 1977.

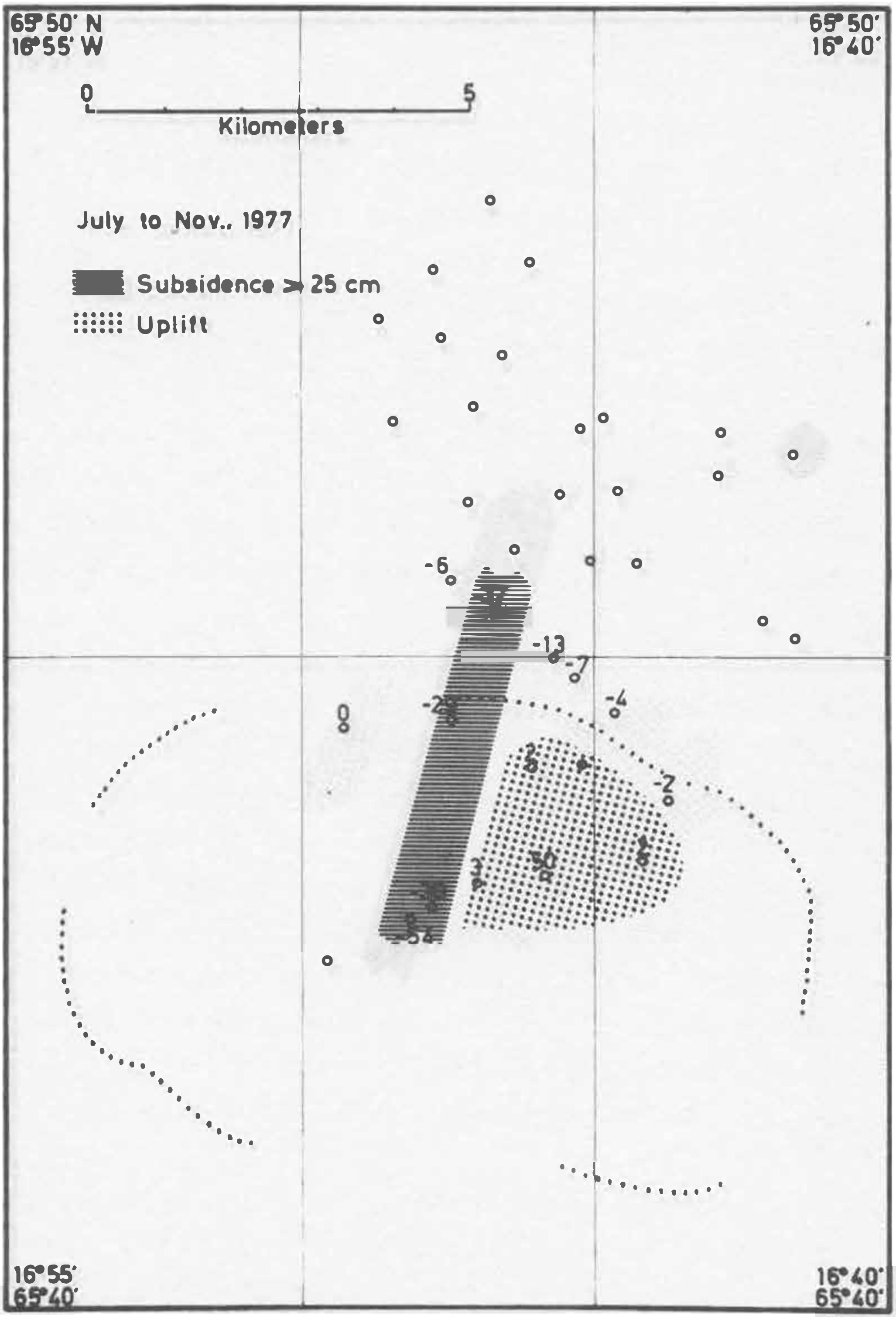


Fig. 7. Observed elevation changes of bench marks in the Gjástykki network between measurements in July and October/November, 1977.

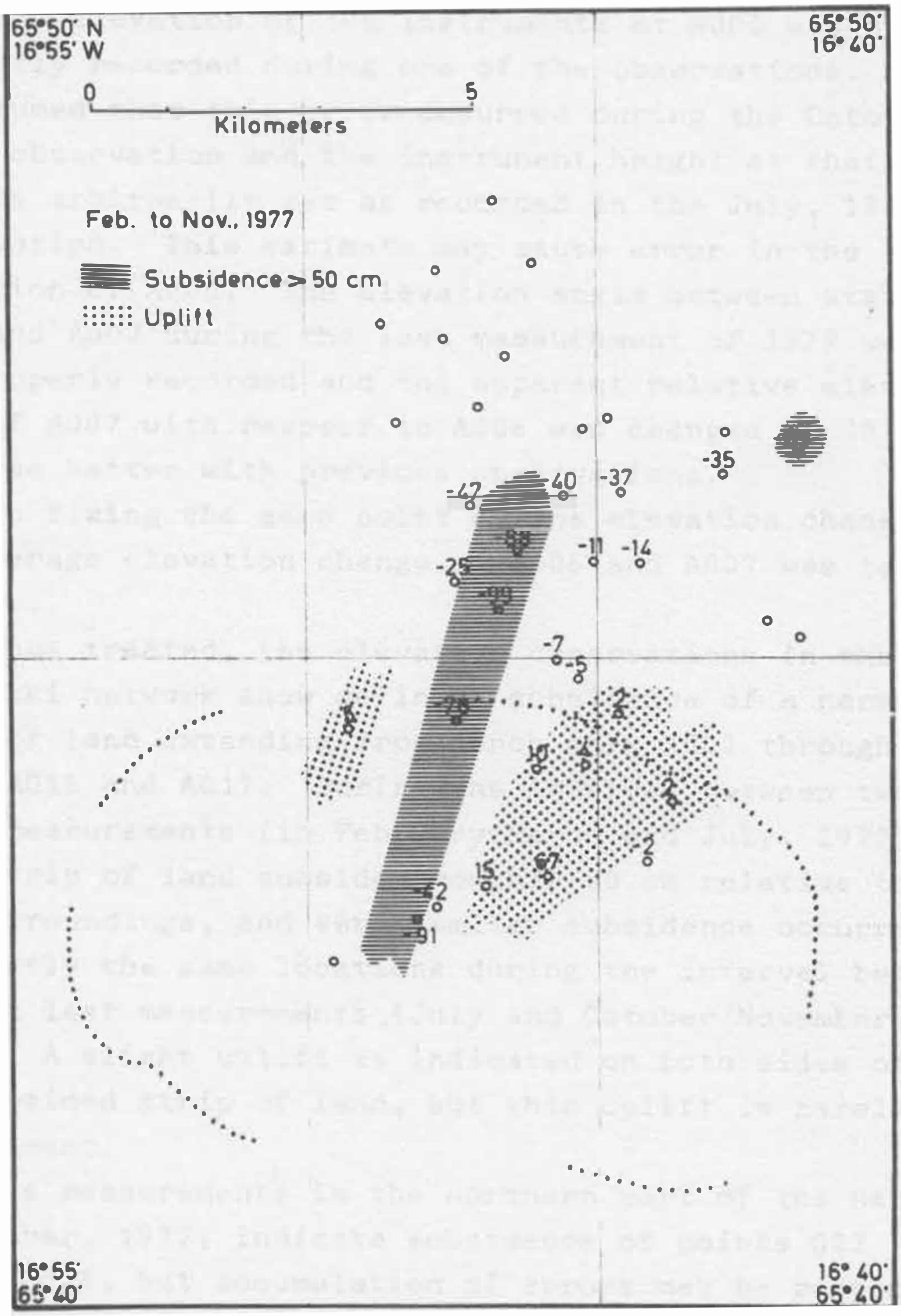


Fig. 8 Observed elevation changes of bench marks in the Gjástykki network between measurements in February and October/November, 1977.

The elevation of the instruments at A005 was not correctly recorded during one of the observations. It is assumed that this error occurred during the October, 1977, observation and the instrument height at that time is arbitrarily set as recorded in the July, 1977, observation. This estimate may cause error in the elevation of A005. The elevation angle between stations A006 and A007 during the last measurement of 1977 was not properly recorded and the apparent relative elevation of A007 with respect to A006 was changed by 30 cm to agree better with previous observations.

In fixing the zero point of the elevation change, the average elevation change of A006 and A007 was taken as zero.

Thus treated, the elevation observations in the Gjástykki network show definite subsidence of a narrow strip of land extending from bench mark A002 through A010, A015 and A017. During the interval between two first measurements (in February/March and July, 1977) this strip of land subsided roughly 50 cm relative to its surroundings, and very similar subsidence occurred at exactly the same locations during the interval between the two last measurements (July and October/November, 1977). A slight uplift is indicated on both sides of the subsided strip of land, but this uplift is barely significant.

The measurements in the northern part of the network in October, 1977, indicate subsidence of points 022 through 026, but accumulation of errors may be responsible for this apparent subsidence.

Correlation with volcano-tectonic events of the area indicate that the subsidence of the narrow strip of land between A002 and A017 occurred during the two volcanic and rifting episodes which occurred, one on April 27-28, 1977, and the other on September 8-9, 1977, and that effect of both episodes were nearly identical in the area of these observations.

RESULT OF DISTANCE MEASUREMENTS IN THE GJÁSTYKKI NETWORK

The measured distances in the Gjástykki network are given in tables 2 through 5, Appendix I, and the changes in distances between measurements are shown on Fig. 9, 10 and 11.

The observed changes of distances are supposedly due to two reasons, either due to elastic streaching or compression, or due to ground displacements on faults or fissures.

The changes in distances between measurements in February, 1977, and July, 1977, are largely due to displacements. Fissures in the western part of the network have opened to cause east-west widening of the fissure system amounting to some 70 cm while the eastern part of the network has been compressed slightly in east-west direction. A large portion of this deformation has certainly occurred during the subsidence event of April 27 to 29 (Björnsson et al., 1978; Tryggvason, 1978), although some horizontal deformation must associate the swelling of the Krafla caldera between subsidence events (Fig. 9).

Another subsidence event occurred on September 8, 1977, and the deformation between the July measurements and the October measurements is primarily from that event. It is noteworthy, that the horizontal component of deformation in the Gjástykki network is almost identical for these two subsidence events (Fig. 10).

An argument for the assumption that most of the deformation between measurements occurred during the subsidence events is that the inflation of the Krafla caldera was at similar stage for all three measurements (Björnsson et al., 1978).

The total widening of the active fissure zone which goes through the western part of the network has been about 1.5 meter from February to October 1977, while compaction of a few centimeter is observed in the eastern part of the network (Fig. 11).

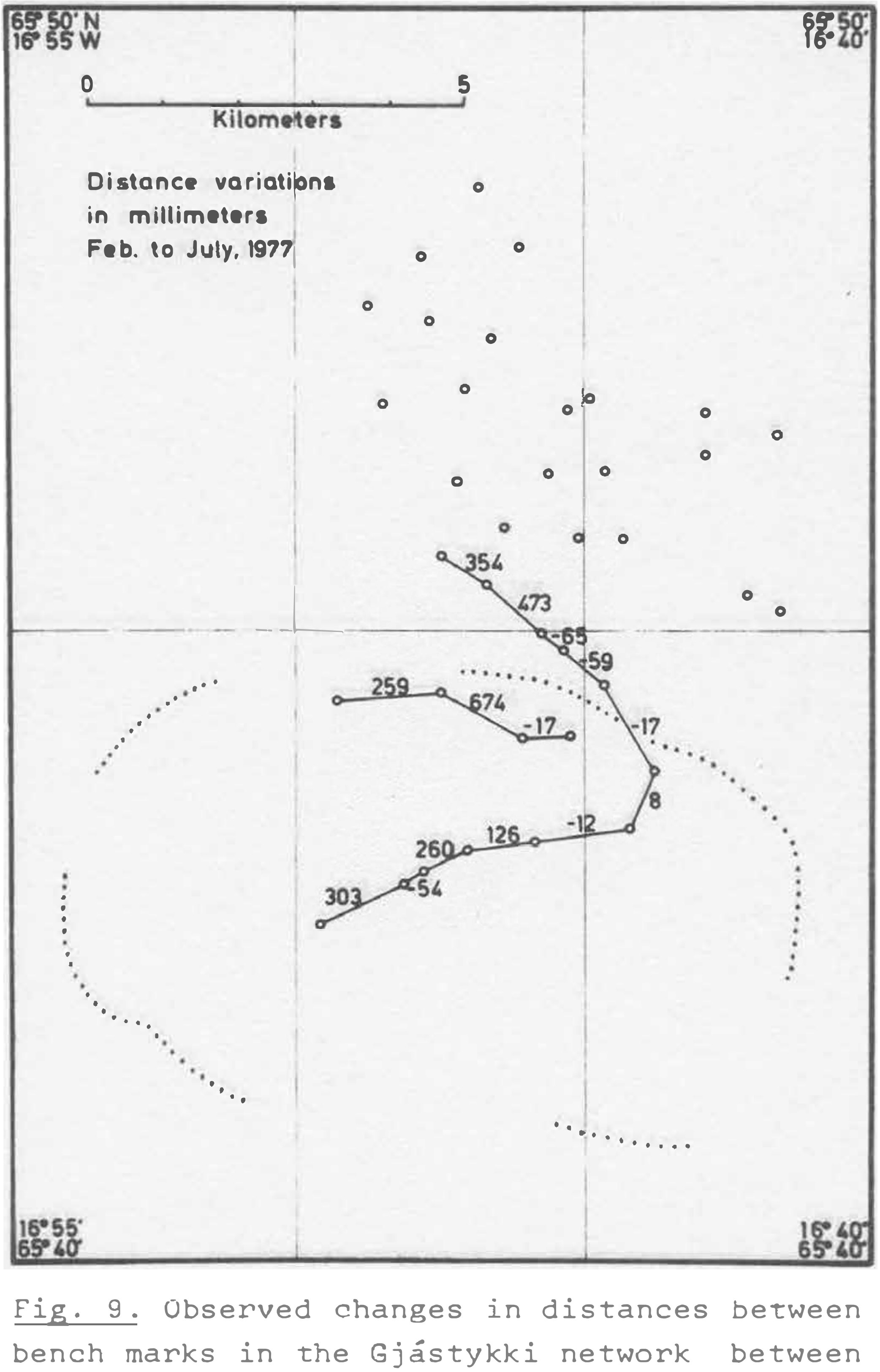


Fig. 9. Observed changes in distances between bench marks in the Gjástykki network between measurements in February and July, 1977.

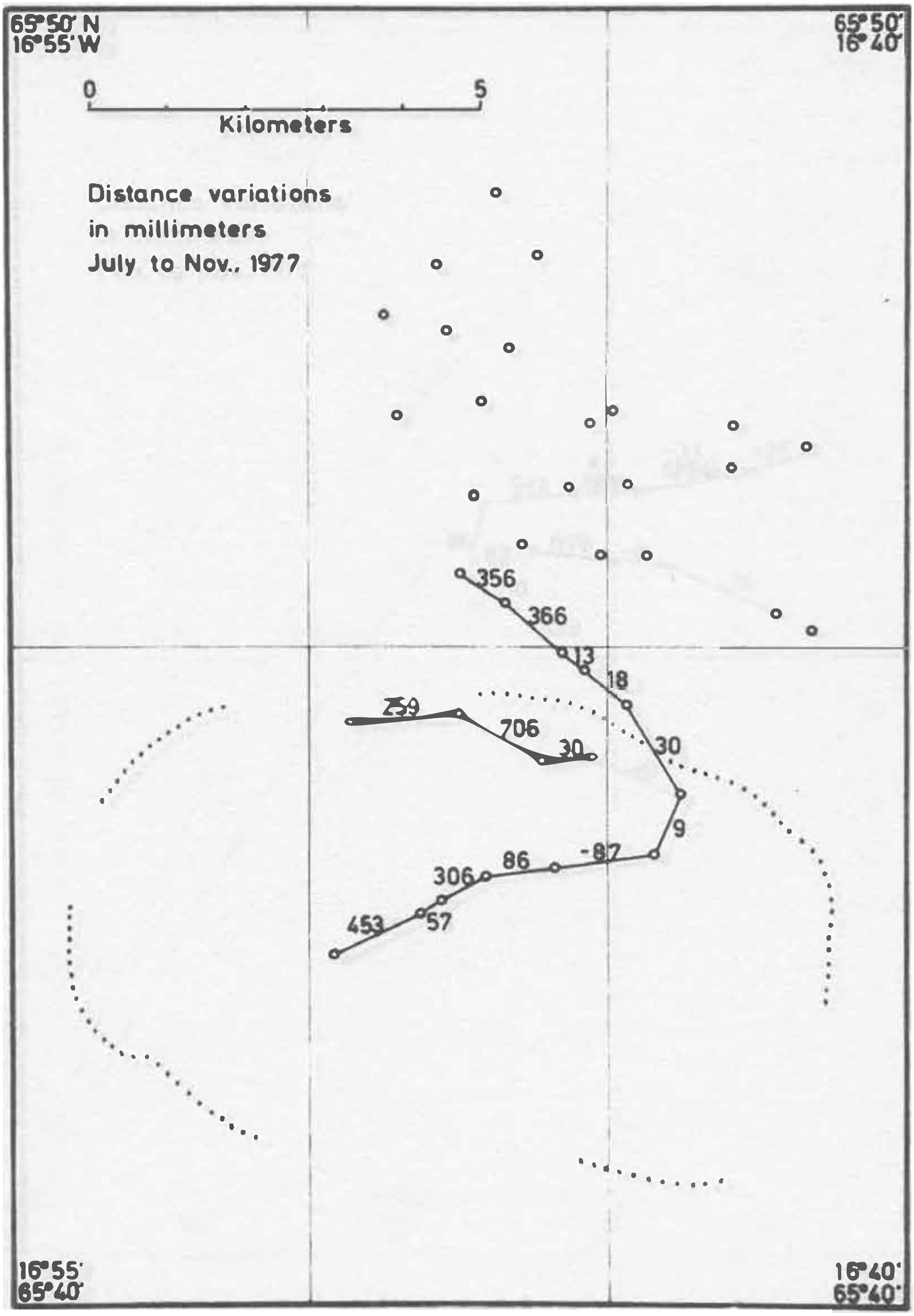


Fig. 10. Observed changes in distances between bench marks in the Gjástykki network between measurements in July and October/November, 1977.

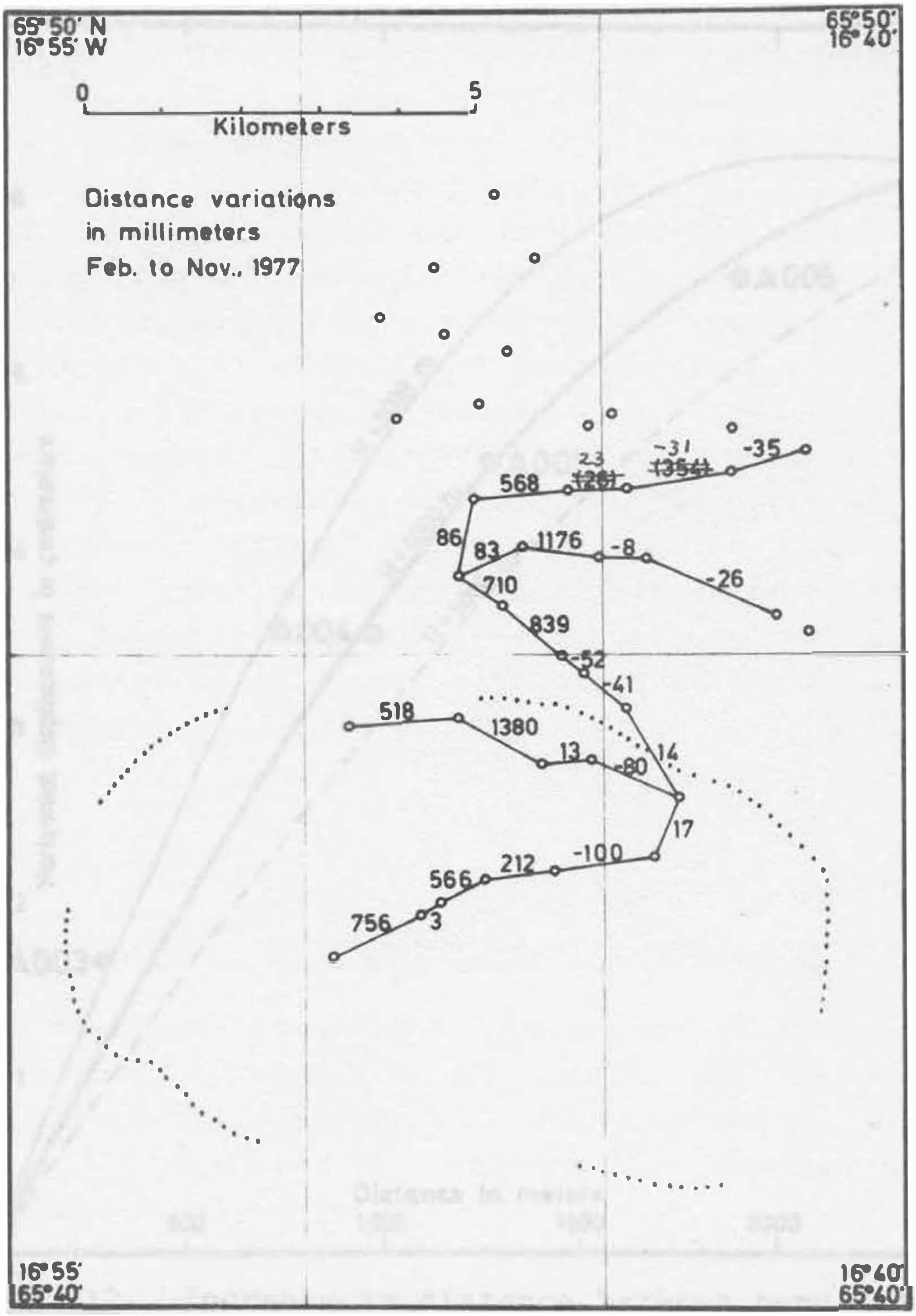
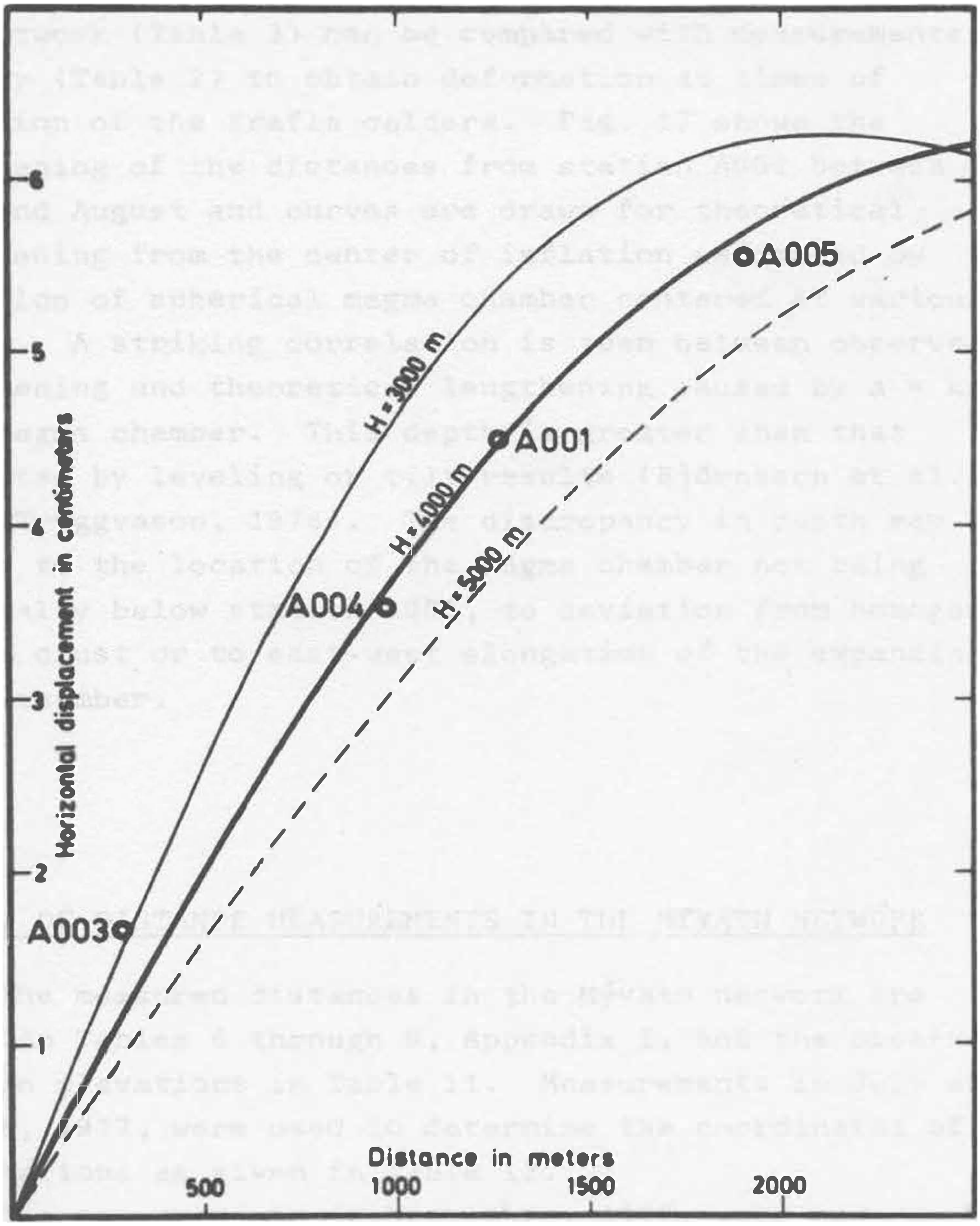


Fig. 11. Observed changes in distances between bench marks in the Gjástykki network between measurements in February and October/November, 1977.



<u>Fig. 12.</u> Increase in distance between bench mark A002 and the bench marks A003, A004, A005 and A006 against distance to these bench marks from A002 from July 19 to August 14, 1977. Curves are drawn for theoretical lengthening in a Mogi model with expanding sphere at 3000, 4000 and 5000 m depth below A002 and an elevation increase of A002 equal 16.27 cm in accordance with tilt measurements at Krafla power house.

Measurements in August 1977 along a small segment of the network (Table 3) can be compared with measurements in July (Table 2) to obtain deformation at times of inflation of the Krafla caldera. Fig. 12 shows the lengthening of the distances from station A002 between July and August and curves are drawn for theoretical lengthening from the center of inflation as caused by expansion of spherical magma chamber centered at various depths. A striking correlation is seen between observed lengthening and theoretical lengthening caused by a 4 km deep magma chamber. This depth is greater than that indicated by leveling or tilt results (Björnsson et al., 1978; Tryggvason, 1978). The discrepancy in depth may be due to the location of the magma chamber not being vertically below station A002, to deviation from homogeniety of the crust or to east-west elongation of the expanding magma chamber.

RESULT OF DISTANCE MEASUREMENTS IN THE MÝVATN NETWORK

The measured distances in the Mývatn network are shown in Tables 6 through 9, Appendix I, and the observed station elevations in Table 11. Measurements in July and August, 1977, were used to determine the coordinates of the stations as given in Table 12.

The measurements in September, 1977, were made immediately after the September 8 subsidence event and Table 13 and Fig. 13 show the displacement of stations during that event. It is clear that rifting extended from north beyond the line Stóragjá-Námafjall but no or insignificant rifting occurred at Hverfjall. The maximum observed widening of the active fissure zone was about 1.1 m, and if results of the Mývatn network and the Gjástykki network (Fig. 10) are combined, it becomes clear that during the September 8 subsidence event, rifting has occurred from somewhere between Bjarnarflag and Hverfjall in the south to beyond station A016 in the north. The length of this zone where widening occurred during this event exceeds 14 km and the widening ranged from 0.7 to 1.1 m.

The flanks of the active fissure zone were compressed in east-west direction as is clearly evidenced by the shortening of the line Stóragjá-Vindbelgur by 25 cm or $35x10^{-6}$ of the total length.

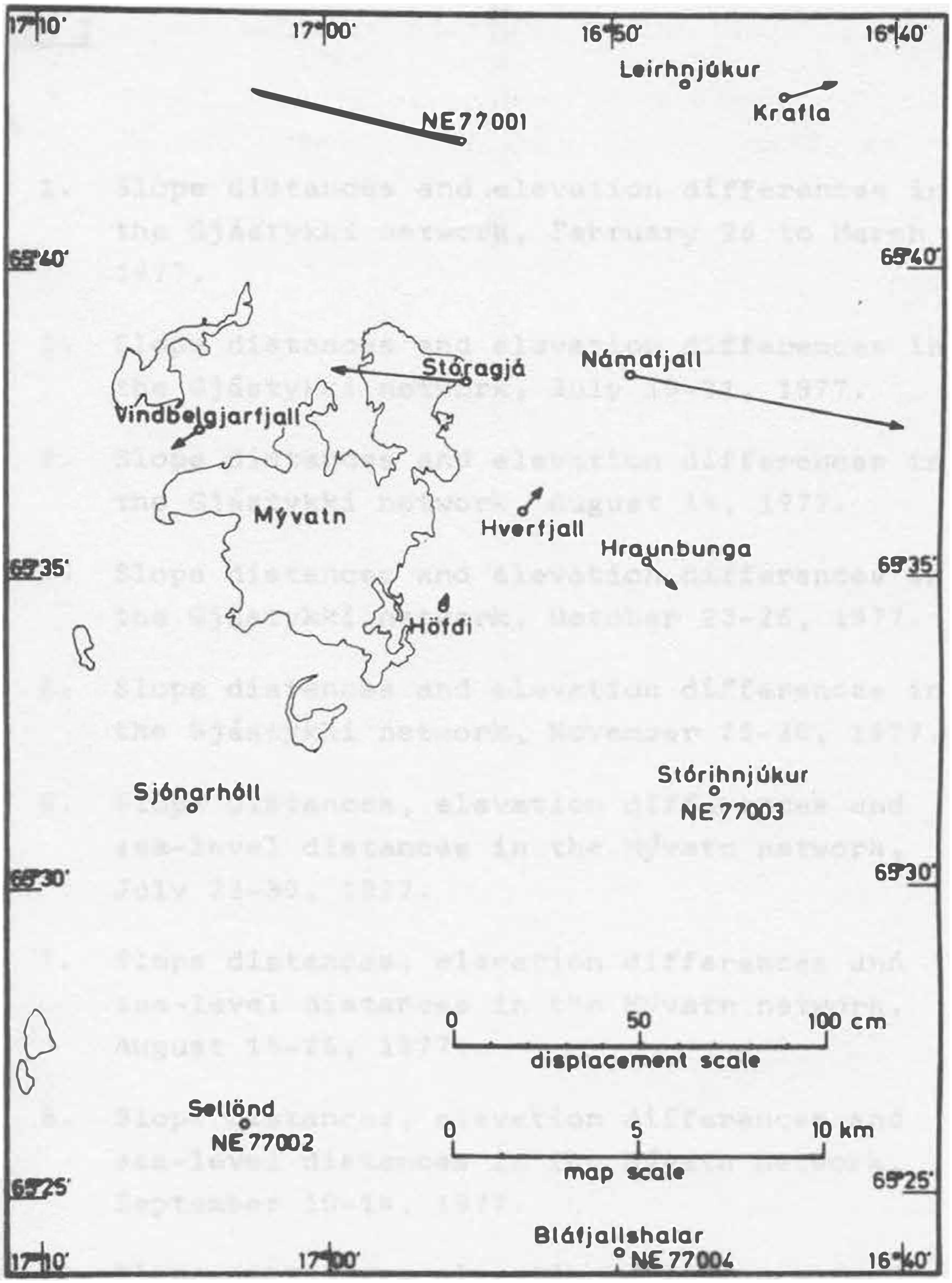


Fig. 13. Observed horizontal displacements of bench marks in the northern part of the Mývatn network from July/August to September, 1977.

APPENDIX I

Tables

Table 1. Slope distances and elevation differences in the Gjástykki network, February 26 to March 3, 1977.

Table 2. Slope distances and elevation differences in the Gjástykki network, July 19-21, 1977.

Table 3. Slope distances and elevation differences in the Gjástykki network, August 14, 1977.

Table 4. Slope distances and elevation differences in the Gjástykki network, October 23-26, 1977.

Table 5. Slope distances and elevation differences in the Gjástykki network, November 25-30, 1977.

Table 6. Slope distances, elevation differences and sea-level distances in the Mývatn network, July 23-30, 1977.

Table 7. Slope distances, elevation differences and sea-level distances in the Mývatn network, August 15-25, 1977.

Table 8. Slope distances, elevation differences and sea-level distances in the Mývatn network, September 10-14, 1977.

Table 9. Slope distances, elevation differences and sea-level distances in the Mývatn network in October and December, 1977.

Table 10. Sea-level elevation of stations in the Gjástykki network.

Table 11. Sea-level elevation of stations in the Mývatn network.

TABLE 1

Slope distances and elevation differences in the Gjástykki network, February 26 to March 3, 1977.

Stations	Slope distance m	Elevation difference m
A001-A002	1265.776	50.28
A002-A003	292.895	1.92
A003-A004	681.575	-44.80
A004-A005	929.298	13.12
A005-A006	1273.598	118.45
A005-A009	1564.023	13.79
A006-A007	929.085	46.94
A007-A008	1231.676	-147.28
A007-A012	1429.237	-48.31
A008-A009	637.627	-4.50
A009-A010	1259.350	24.18
A010-A011	1389.558	-61.27
A010-A012	2162.398	79.31
A012-A013	750.188	-54.24
A013-A014	443.669	-20.32
A014-A015	1024.752	-59.38
A015-A016	710.235	-23.89
A016-A017	943.905	33.81
A016-A022	1141.405	1.66
A017-A018	987.960	52.83
A018-A019	616.549	29.09
A019-A020	1825.436	36.96
A020-A021	484.327	38.85
A020-A025	2159.126	-112.89
A022-A023	1009.161	52.37
A023-A024	750.147	69.68
A024-A025	1336.630	-83.84
A025-A026	1017.539	77.07
A026-A027	986.441	-105.67
A027-A028	1550.618	-5.53

A028-A029	349.720	22.68
A028-A032	1119.364	-30.39
A029-A030	1427.286	-7.46
A030-A031	1090.163	-29.33
A032-A033	1336-678	26.18
A033-A034	846.932	-11.09
A034-A035	1020.120	-3.23
A035-A036	1274.086	-27.66
A035-A038	1248.909	-23.85

TABLE 2

Slope distances and elevation differences in the Gjástykki network, July 19-21, 1977.

Stations	Slope distance m	Elevation difference m
A001-A002	1266.079	49.72
A002-A003	292.840	2.17
A003-A004	681.835	-44.65
A004-A005	929.424	13.25
A005-A006	1273.586	118.24
A006-A007	929.093	47.00
A007-A012	1429.221	-48.28
A008-A009	637.610	
A009-A010	1260.024	23.63
A010-A011	1389.816	-60.74
A012-A013	750.129	-54.27
A013-A014	443.604	-20.29
A014-A015	1025.226	-60.05
A015-A016	710.590	-23.45

TABLE 3

Slope distances and elevation differences in the Gjástykki network, August 14, 1977.

Stations	Slope distance m	Elevation difference m
A001-A002	1266.122	49.81
A002-A003	292.857	2.16
A003-A004	681.853	-44.56
A004-A005	929.444	13.17

TABLE 4

Slope distances and elevation differences in the Gjástykki network, October 23-26, 1977.

Stations	Slope distance m	Elevation difference m
A001-A002	1266.532	
A002-A003	292.898	2.40
A003-A004	682.141	-44.28
A004-A005	929.510	13.69
A005-A006	1273.499	117.76
A006-A007	929.101	47.33
A007-A008	1231.596	-147.25
A007-A012	1429.251	-48.29

TABLE 5

Slope distances and elevation differences in the Gjástykki network, November 25-30, 1977.

Stations	Slope distance m	Elevation difference m
A008-A009	637.640	-4.45
A009-A010	1260.730	23.32
A010-A011	1390.075	-60.46
A012-A013	750.147	-54.31
A013-A014	443.617	-20.34
A014-A015	1025.591	-60.30
A015-A016	710.945	-23.15
A016-A017	943.988	33.15
A016-A022	1141.491	1.43
A017-A018	989.136	53.63
A018-A019	616.541	29.07
A019-A020	1825.410	
A022-A023	1009.729	52.44
A023-A024	750.173	69.71
A024-A025	1336.984	-83.83
A025-A026	1017.504	76.73

TABLE 6

Slope distances, elevation differences and sea-level distances in the Mývatn network, July 23 to 30, 1977.

Stations	Slope distance m	Elevation difference m	Horizontal sea-level distance m
Námafjall-Stóragjá	4349.188	-178.63	4345.251
Námafjall-Hverfjall	5095.254	-37.91	5094.740
Höfði-Hraunbunga	6235.537	186.51	6232.355
Höfði-Hverfjall	3629.945	135.94	3627.179
Höfði-Stórihnjúkur	10122.841	471.97	10110.969
Höfði-Vindbelgur	7391.580	220.21	7387.803
Höfði-Sjónarhóll	9011.856	19.20	9011.385
Höfði-Stóragjá	6296.440		6296.137
Hverfjall-Hraunbunga	3554.912	50.55	3554.292
Hverfjall-Stóragjá	4322.389	-140.34	4319.862
Sjónarhóll-Stórihnjúkur	14014.607	451.83	14006.106
Sjónarhóll-Vindbelgur	11364.481	200.88	11361.952
Stóragjá-Vindbelgur	7249.660		7245.702
NE77001-Krafla	8764.332	231.74	8760.308
NE77001-Námafjall	8408.712	-101.22	8407.396
NE77001-Stóragjá	7365.832	-280.50	7359.989
NE77001-Leirhnjúkur	6126.202	5.70	6125.636
Námafjall-Vindbelgur	11562.933	45.73	11561.926

TABLE 7

Slope distances, elevation differences and sea-level distances in the Mývatn network, August 15 to 25, 1977.

Stations	Slope distance m	Elevation difference m	Horizontal sea-level distance m
Námafjall-Stóragjá	4349.206	-178.66	4345.269
Námafjall-Hraunbunga	5733.593	13.55	5733.142
Námafjall-Krafla	9282.444	332.69	9275.515
Höfði-Hraunbunga	6235.548	186.75	6232.355
Sjónarhóll-Sellönd	9686.607	100.71	9685.554
Sellönd-Bláfjallshalar	10729.619	506.90	10719.494
Sellönd-Stórihnjúkur	16116.232	355.67	16110.800
Stórihnjúkur-Bláfj.halar	14172.991	152.03	14170.278
Stórihnjúkur-Hraunbunga	7152.334	-285.48	7145.920
NE77001-Vindbelgur	11230.683	-56.00	11229.568

TABLE 8

Slope distances, elevation differences and sea-level distances in the Mývatn network, September 10 to 14, 1977.

Stations	Slope distance m	Elevation difference m	Horizontal sea-level distance m
Námafjall-Stóragjá	4350.255	-178.27	4346.320
Námafjall-Hraunbunga	5733.425	12.32	5732.974
Námafjall-Hverfjall	5095.438	-38.18	5094.924
Námafjall-Krafla	9282.289	333.59	9275.361
Námafjall-NE77001	8409.577	102.42	8408.261
NE77001-Stóragjá	7365.940	-279.62	7360.098
NE77001-Krafla	8765.107	231.22	8761.084
NE77001-Vindbelgur	11230.597	-57.24	11229.482
Höfði-Hverfjall	3629.992	136.27	3627.229
Höfði-Stóragjá	6296.374	-3.83	6296.071
Höfði-Vindbelgur	7391.612	220.39	7387.836
Höfði-Hraunbunga	6235.612	186.30	6232.431
Hverfjall-Hraunbunga	3555.062	50.75	3554.382
Hverfjall-Stóragjá	4322.521	-141.28	4319.994
Stóragjá-Vindbelgur	7249.406	224.46	7245.447

TABLE 9

Slope distances, elevation differences and sea-level distances in the Mývatn network in October and December 1977.

Stations	Slope distance m	Elevation difference m	Horizontal sea-level distance m
October 23-25, 1977			
Námafjall-Stóragjá	4350.255		4346.320
Námafjall-Sandfell	3157.061	-87.07	3155.643
Stóragjá-Dalfjall W	4533.578	174.86	4529.926
Dalfjall W-Dalfjall E	697.539	11.53	697.386
Dalfjall E-Sandfell	2520.782	-95.55	2518.808
December 3, 1977			
Stóragjá-B003	1889.172	15.77	1889.014
Stóragjá-Námafjall	4350.259	178.71	4346.316

TABLE 10

Sea-level elevation of stations in the Gjástykki network, Feb. 26 to March 3, 1977 assuming 542.00 m at station A001.

Station	Elevation m	Station	Elevation m
A001	542.00	A020	674.47
A002	592.28	A021	713.32
A003	594.19	A022	523.43
A004	549.39	A023	575.80
A005	562.51	A024	645.48
A006	680.96	A025	561.63
A007	727.89	A026	638.70
A008	580.61	A027	533.03
A009	576.11	A028	527.49
A010	600.29	A029	549.17
A011	539.02	A030	542.71
A012	679.60	A031	513.38
A013	625.36	A032	497.11
A014	605.04	A033	523.28
A015	545.66	A034	512.19
A016	521.78	A035	508.96
A017	555.59	A036	481.30
A018	608.42	A037	
A019	637.51	A038	485.11

TABLE 11

Sea-level elevation of stations in the Mývatn network.

Station	Elevation m
Stórihnjúkur	78C.1
Höfði	308.1
Sjónarhóll	328.3
Vindbelgur	528.7
Hverfjall	444.1
Námafjall	482.5
Stóragjá	303.9
Hraunbunga	494.6
NE77001	584.1
Krafla	815.8
Leirhnjúkur	589.8
Sellönd	425
Bláfjallshalar	932
Sandfell	395.4
Dalfjall W	478.8
Dalfjall E	490.6
B003	319.7

TABLE 12

Coordinates of stations in the Mývatn network at sea-level in July and August 1977.

Stations	North m	East m
Sjónarhóll[x)]	0.000	0.000
Vindbelgur[x)]	241.295	11359.390
Sellönd	1458.269	-9575.145
Bláfjallshalar	11471.837	-13400.883
Stórihnjúkur	13995.588	542.849
Hraunbunga	12185.795	7455.796
Höfði	5996.219	6726.843
Hverfjall	8924.060	8867.910
Stóragjá	7325.408	12881.078
Námafjall	11661.386	13164.821
NE77001	7116.803	20238.110
Krafla	15789.986	21470.833
Leirhnjúkur	13008.520	21914.742

[x)] The zero-point of the Coordinate system is placed at the station Sjónarhóll, geographic coordinates 65°31´20.853"N, 17°04´29.43"W in the Icelandic geodetic network, and the orientation of the coordinate axes is based on the location of Vindbelgjarfjall (Vindbelgur), geographic coordinates 65°37´27.615"N, 17°04´10.42"W.

TABLE 13

Displacements of geodimeter stations in the Mývatn network from July/August 1977 to September 1977 in centimeters.

Stations	Assumption I[x)]		Assumption II[x)]		Assumption III[x)]	
Vindbelgur	0.0	0.0	-11.2	8.1	-8.9	-5.9
Höfði	2.8	-1.7	-8.4	6.4	1.6	2.0
Stóragjá	-25.6	-2.2	-36.8	5.9	-37.0	3.7
Hverfjall	9.8	-2.6	-1.4	5.5	5.1	5.9
Hraunbunga	11.1	-22.4	-0.1	-14.3	8.7	-8.4
Námafjall	83.2	-28.5	72.0	-20.4	71.3	-15.4
NE77001	-33.2	8.8	-44.4	16.9	-56.8	14.3
Krafla	41.1	-16.5	29.9	-8.4	15.5	3.4

[x)] Assumption I is: Vindbelgur fixed and direction Vindbelgur-Höfði fixed. Assumption II is: Sum of displacements zero in both X- and Y-direction, direction Vindbelgur-Höfði fixed. Assumption III is: Sum of displacements zero in both X- and Y-direction, sum of rotation of stations around the center of gravity equal zero.

APPENDIX II

Correction for refraction of light

The velocity of light in air depends on the air density, and as the density varies with altitude, a near norizontal light ray will follow a curved path. Elevation differences determined with trigonometry, using theodolite, should be corrected for this light refraction for highest accuracy.

The radius of curvature r of a light ray travelling in a media of varying index of refraction, n, is given by the equation:

$$r = n/(dn/dr) \qquad (II,1)$$

The index of refraction of light in air depends on the air density and the wave length. For any given wave length of light, the value of 1-n in air is proportional to the air density with a proportionality constant a_λ depending on the wavelength of light:

$$n - 1 = a_\lambda \rho \qquad (II,2)$$

If the density (ρ) of air is given in g cm^{-2} the constant a_λ becomes (Weast et al., 1964)

0.2298 for 4000 angstrom wavelength,
0.2268 for 5000 angstrom wavelength,
0.2254 for 6000 angstrom wavelength, and
0.2246 for 7000 angstrom wavelength.

The density of air is a function of its temperature, pressure, and humidity. For dry air, this function is given by

$$\rho = \frac{0.001293}{1 + 0.00367\,T} \cdot \frac{\quad}{760} \qquad (II,3)$$

where the density (ρ) is in g cm^{-2}, the temperature (T) in °C and the pressure (P) in mm Hg. The density gradient $d\rho/dr$ is derived from (II,3) as:

$$d\rho/dr = A\,dT/dr + B\,dP/dr \qquad (II,4)$$

where:

$$A = -\frac{6.244 \cdot 10^{-9} P}{(1 + 0.00367\,T)^2} \qquad \text{(II.5)}$$

and:

$$B = \frac{1.701 \cdot 10^{-6}}{1 + 0.00367\,T} \qquad \text{(II.6)}$$

The values of A and B in (II,4) are given in Table II,1 for selected values of temperature and pressure.

TABLE II,1

Values of A and B in equation (I,4) for selected values of the temperature T and the pressure P.

T	P	-A	B
-10	760	$5.114 \cdot 10^{-6}$	$1.833 \cdot 10^{-6}$
0	760	4.745	1.701
10	760	4.415	1.583
-10	700	4.710	1.833
0	700	4.371	1.701
10	700	4.067	1.583

The vertical gradient of atmospheric pressure dP/dz is proportional to the air density. If the density is given in g cm^{-2} and the pressure in mm Hg, the vertical pressure gradient becomes:

$$dP/dz = -\rho/1.358 \text{ mm Hg/cm} \qquad \text{(II.7)}$$

The vertical temperature gradient dT/dz is variable, but its average value in Iceland vary with time of year and location between -4×10^{-5} and -8×10^{-5} °C/cm (Eythorsson & Sigtryggsson, 1971). The vertical density gradient $d\rho/dz$ may be obtained from (II,4) using (II,3), (II,7) and data given in Table I,1. The density gradient thus obtained is given in Table II,2 for selected values of the temperature, T, pressure, P, and temperature gradient dT/dz.

TABLE II,2

Values of the density gradient $d\varrho/dz$ in g cm^{-2} per cm for selected values of T, P and dT/dz.

T	P	$d\varrho/dz$ $dT/dz=4\cdot10^{-5}$	$dT/dz=6\cdot10^{-5}$	$dT/dz=8\cdot10^{-5}$
-10	760	$-1.607\cdot10^{-9}$	$-1.505\cdot10^{-9}$	$-1.403\cdot10^{-9}$
0	760	-1.430	-1.335	-1.240
10	760	-1.277	-1.189	-1.101
-10	700	-1.480	-1.386	-1.292
0	700	-1.317	-1.230	-1.143
10	700	-1.177	-1.095	-1.013

From equations (II,1) and (II,2) we get that the radius of curvature of a horizontally travelling light ray as

$$r = \frac{n}{a_\lambda \cdot d\varrho/dz} \qquad \text{(II,8)}$$

For light of 5000 angstrom wave length we get that the radius of curvature is $2.74\cdot10^9$ to $4.35\cdot10^9$ centimeter for the temperature and pressure conditions of Table II,2. Correction of vertical angle for this refractive bending of the light ray amounts to $\frac{D}{2r}$ where D is the distance from the theodolite to the target. In geodetic work as described in the present report, most measuring lines are nearly horizontal, so radius of curvature of the light ray may be taken from equation (I,8). An average value for the radius of curvature of the light ray appears to be roughly $3.5\cdot10^9$ cm and the correction of the vertical angle then becomes:

$$\Delta\varphi \approx \frac{D}{7\cdot10^7} \text{ radians} \qquad \text{(II,9)}$$

if D is the sight distance in meters. This correction is accepted in the present report.

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