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Experience of Motorized Trigonometric Levelling (MTL) - a comparison with other techniques

by Jean-Marie Becker
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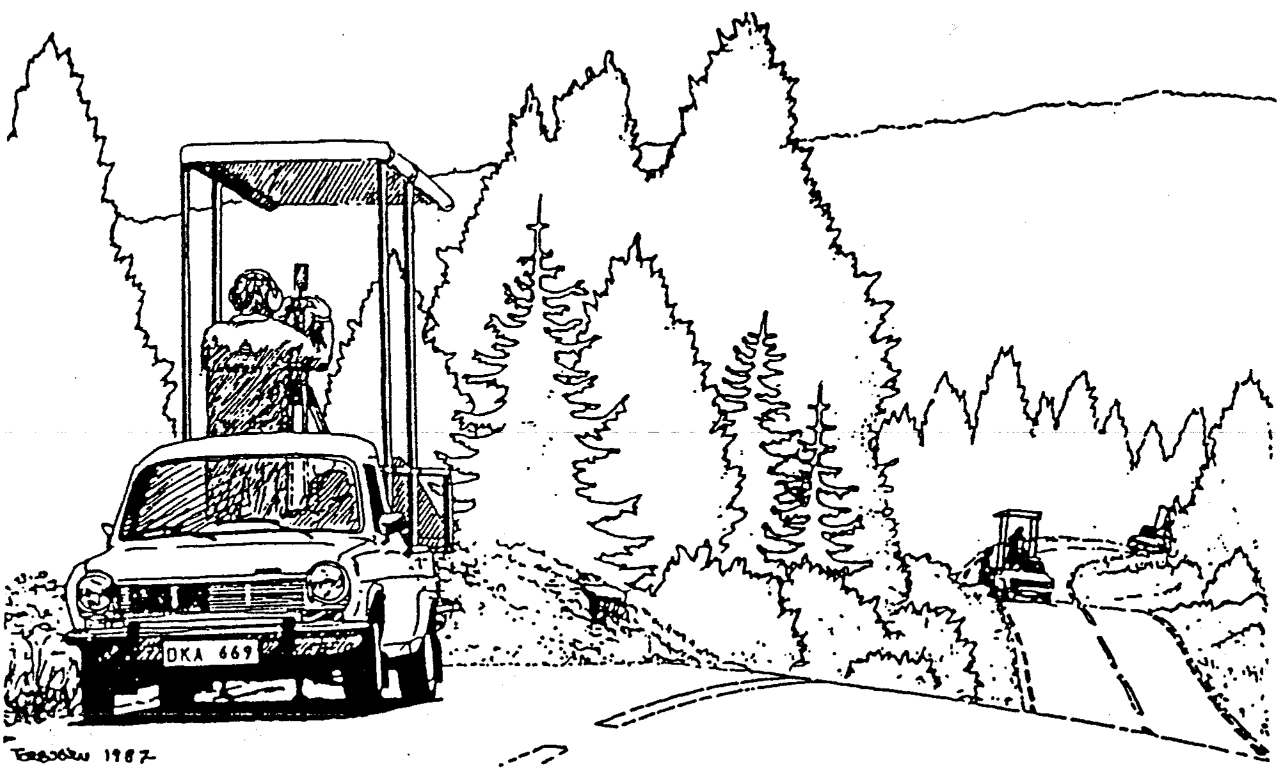

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Experience of Motorized Trigonometric Levelling (MTL) - a comparison with other techniques

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Huvudinnehåll - Main Contents

The report gives the results of tests using Motorized Trigonometric Levelling (MTL) during the period 1985-87.

(Rapporten är en översättning till Engelska av LMV-rapporten 1988:12; "Erfarenheter med motoriserad trigonometrisk höjbestämningsteknik (MTL) - jämförelser med övriga tekniker")

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CONTENTS

1. INTRODUCTION

The project "riksavvägning" (RA) - National Precise Levelling Programme - has been in progress since 1979. The aim of the project is to determine a new national precise levelling net encompassing approximately 50,000 km. The work is well under way and completion is estimated to be around the year 1997. The National Land Survey (NLS), which is responsible for this project, has developed a specially adapted technique known as the Motorized Levelling Technique (ML) [6].

As work on the project has been carried out, certain problems have arisen which need to be explained and solved, for example, the systematic effects of geomagnetism and abnormal differences between the 2nd and 3rd National Precise Levelling Programmes (RA). At the same time and running parallel to the project, experiments and tests take place continually in order to improve the levelling technique and make it more efficient, for example, through further automation of the surveying process.

This report describes the tests carried out and the results achieved in connection with various investigations during the last 3 years (1985-1987) using Motorized Trigonometric Levelling (MTL).

Experiments with MTL have been carried out in different areas in Sweden and with different objectives as follows:

- investigation of MTL (technique and equipment) with regard to accuracy, using three different makes of instrument (Geotronics, Wild and Kern). Results from the tests are published in [1] - Sätra, Gävle 1985 (spring and autumn).

- production test - Falun 1985.

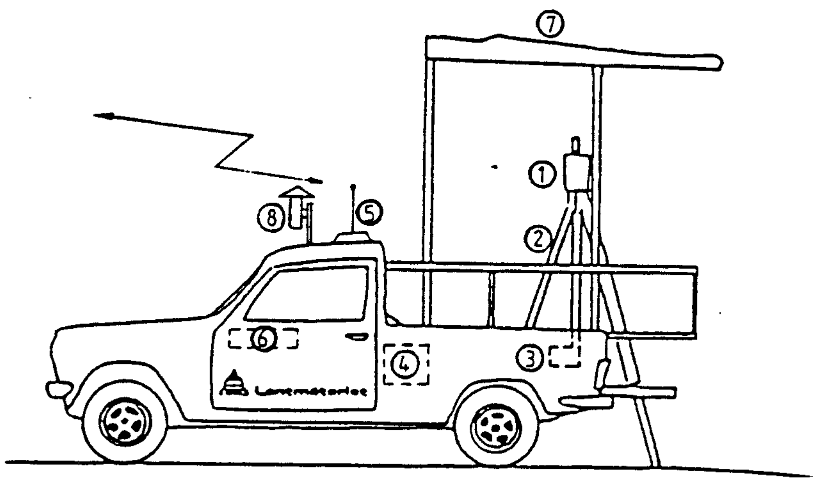
- large scale project using simultaneous observations for comparative studies of MTL and ML - Sälen 1986.

- MTL survey along an older Precision-line to ascertain why the FL result from 1958 (levelling on foot using Wild N3, 2nd precise levelling) differed so much from the ML result from 1981 (motorized levelling, 3rd precise levelling) - Jönköping area 1987.

- tests to simultaneously determine plane co-ordinates (x,y). These tests are not described in the report - Sätra, Gävle 1985 and Älvkarleby 1987.

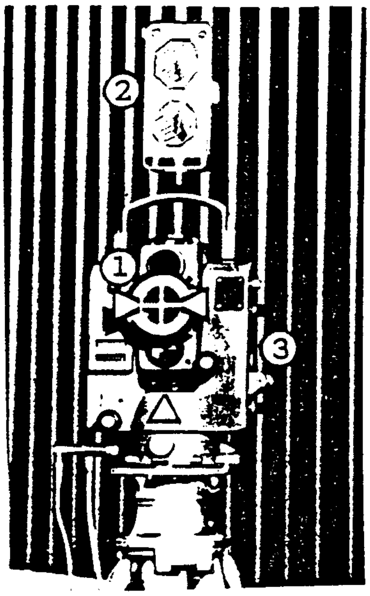
2. EQUIPMENT

In short, the equipment consists of three identical pick-up trucks. Each vehicle is fitted with an electronic total station, tripod and equipment for wireless transmission of survey-data (telemetry). All survey data is collected in a field computer which is in one of the vehicles - the control vehicle (figure 2:1-3).



1 = Total station with vertical target and reflector
2 = Specially constructed tripod with adjustable legs.
3 = Electric hoist
4 = Telemetry equipment
5 = Aerial for reception/transmission
6 = Field computer and printer
7 = Folding sun/rain canopy
8 = Thermometer with inbuilt fan

FIGURE 2:1 Pick-up truck with equipment.



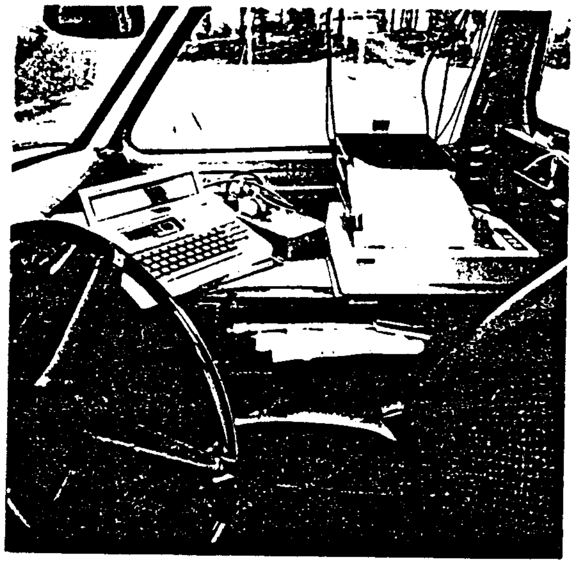


FIGURE 2:2

Total station with vertical target (1), reflector (2) and an extra spirit-level (3).

FIGURE 2:3

Control vehicle with field computer and printer.

Instruments

Each vehicle is equipped with an electronic total station. In Falun, the survey was carried out using Wild T2000 + DI5. In Sälen and Jönköping, Kern E2 + DM 503 was used. The Kern equipment is supplemented with a target for measurement of angles and a reflector for distance measurements. In order to simplify levelling of the instrument, an additional spirit-level is attached (figure 2:2).

The standard error of angles for both instruments is 0.15 mgon and the standard error of the two EDM instruments is 3 mm + 2 ppm.

Tripods

The tripods have been specially constructed by NLS to fit the vehicles. Each tripod is fitted with a device for fast levelling of the instrument. In order to simplify raising and lowering the tripods in connection with transportation, each vehicle is equipped with an electric hoist. Each tripod foot is in the form of a round steel plate which has three spikes (figure 2:4). The plate is joined to the tripod leg by means of a ball and socket joint. This enables the tripod foot to adjust itself to, for example, uneven ground when the equipment is being set up. The construction has been found to give good stability.

The tripods are considerably taller than conventional ones. The average height is about 2.20 m and this reduces substancially the effect refraction has on the results.

The tripods are placed centrally in the back of each vehicle. When the station is set up, the tripod legs are lowered through three holes in the floor of the vehicle. There is no contact between the tripod and the vehicle when surveys are carried out.

Levelling rod

An invar rod (Zeiss Jena 3 m) is used when making bench mark ties. Four vertical targets are mounted on the rod. The distance between the respective targets and the foot plate has been measured by using a laser interferometer. The standard error for these distances is <0.06 mm.

The four targets are mounted at heights of 1.5, 2.0, 2.5 and 3.0 m.

Three spirit-levels, independent of each other are used to facilitate levelling. In addition, the rod is equipped with two adjustable supports (figure 2:5).

Telemetry

Each vehicle has its own telemetry equipment for transmission of survey data. On one of the vehicles (the control vehicle), there is also a radio receiver which transmits all survey data to the field computer.

The equipment consists of a telecommunications modem which transmits/receives survey data via a walkie-talkie.

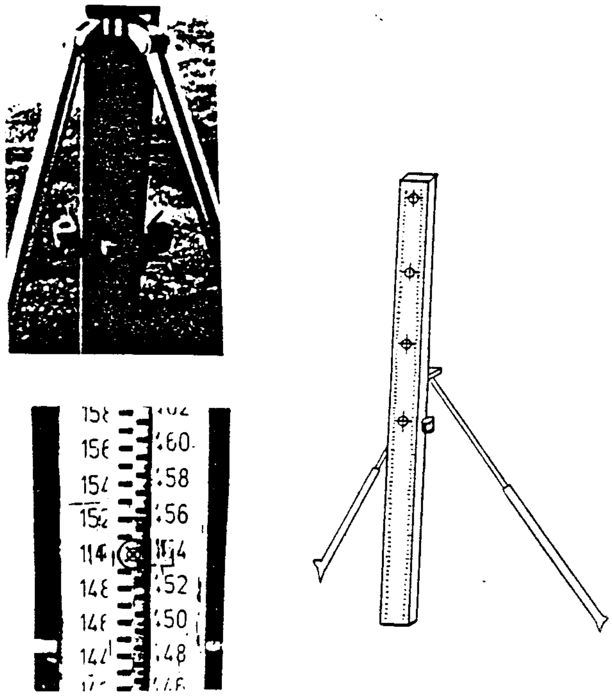


FIGURE 2:4 Tripod foot. FIGURE 2:5 Levelling rod.

Processing of survey data

All recording of data is done automatically by a single push of a button whereby the entire set of observations is transferred via telemetry to a receiver unit in the control vehicle. A field computer (Epson PX8) is connected to this unit. The computer does a number of calculations and gives, amongst other things, information about the quality of observations. The result is printed out on an Epson RX 80 printer. It is also possible to store raw data internally in the computer's memory. The program is written in BASIC and has been developed by NLS.

Other equipment

- Barometer (Baromec)
- Thermometer with inbuilt fan
- Walkie-talkie
- Extra batteries
- Battery charger
- Replacement legs for tripod

3. SURVEYING PROCEDURE

There are two types of levelling procedure. One is when making bench mark ties and the other when elevation differences are observed between the vehicles.

Bench mark ties

When bench mark ties are made, a levelling rod with four vertical targets is used (figure 3:1). The difference in elevation between the instrument and the bench mark is calculated by using the following formula [4]:

$$dH_1 = \frac{h_3 * \cot Z_1 - h_1 * \cot Z_3}{\cot Z_1 - \cot Z_3}$$

The four targets on the rod make it possible to determine two separate elevation differences from which the mean value is calculated. Target 1 and target 3 give the elevation difference dH_1 and target 2 and target 4 give dH_2.

The field computer is used for all computations which include deviation and standard error. The operator makes the decision as to whether the result is acceptable or not.

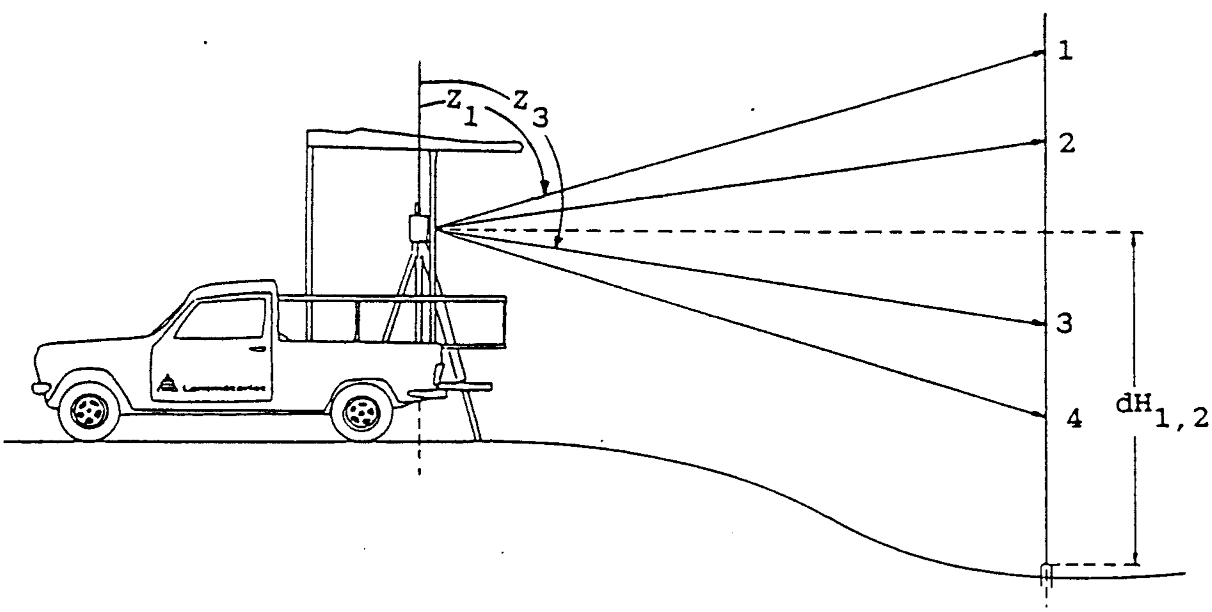


Figure 3:1 Making bench mark ties

Observations between vehicles

In between making bench mark ties, elevation differences are determined between the vehicles (i.e. the instruments). This is done by observing the slope distance from both directions. If the discrepancy between the two observations exceeds 5 mm, the observation is repeated. The vertical angles are observed simultaneously and reciprocally (figure 3:2). The difference in elevation between vehicle A and vehicle B is calculated by using the following formula:

$$dH_{A-B} = \frac{L * (\cos Z_{A-B} - \cos Z_{B-A})}{2}$$

Vertical angles are observed in three sets after which the field computer calculates the mean value and standard error. The operator advises the team whether observations must be repeated or can be accepted. Temperature and air pressure for atmospheric correction are recorded by the operator at the same time as the distances are being measured.

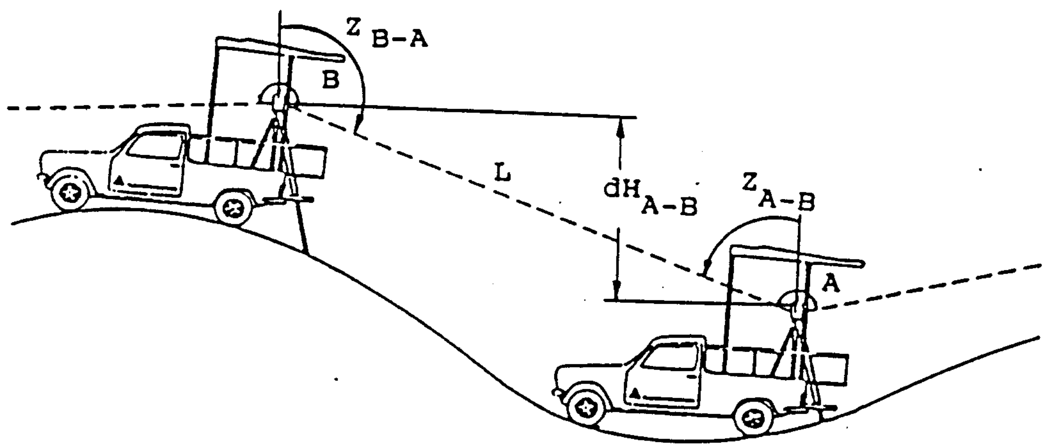


FIGURE 3:2 Observations between vehicles.

4. DESCRIPTION OF THE TEST AREAS

This report gives an account of test surveys from three areas, namely Falun 1985, Sälen 1986 and Jönköping 1987 (figure 4:1).
The three test areas have one thing in common in that the terrain is relatively hilly. Another factor which influenced the choice of the test areas Falun and Jönköping, was that it had previously been established that there were significant contradictions between the 2nd precise levelling with FL and the 3rd precise levelling with ML.

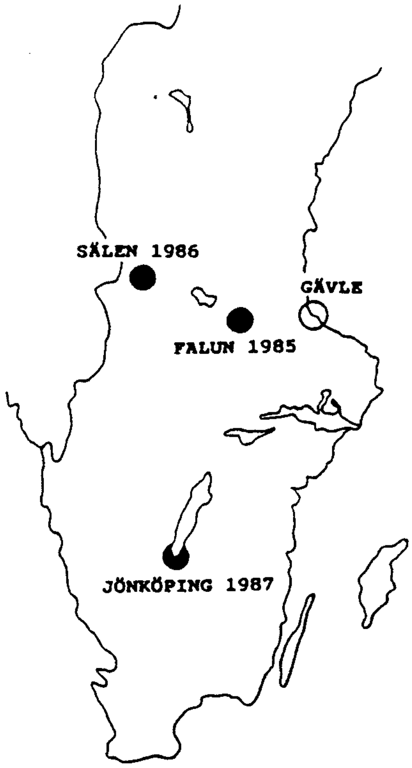


FIGURE 4:1 Test areas.

In Falun, in 1985, the main object of the test survey was to try to ascertain why previously (in 1979) there had been such a high percentage of re-levelling (61%).
At the same time, the production capacity of MTL was also to be tested. In all, a relatively short distance, 17 km, was levelled and the average difference in height between the bench marks was approximately 18 m. In total, 19 sections were levelled.

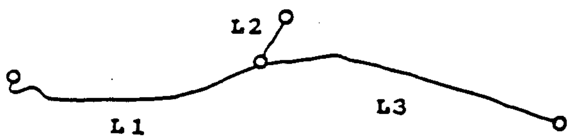


FIGURE 4:2 Falun 1985.

In Sälen, in 1986, a considerably larger area of approximately 192 km was surveyed. Here, the differences in height were also the greatest, as much as 400 m in some cases. A total of 196 sections were levelled. The terrain consisted mainly of forest areas as well as some bare mountain regions above the tree-line. 60% of the roads were tarmac and the remainder were unmade roads

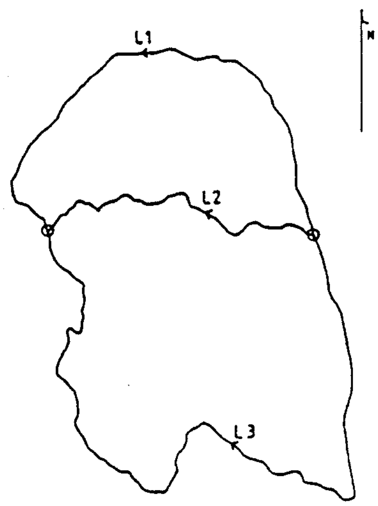


FIGURE 4:3 Sälen 1986.

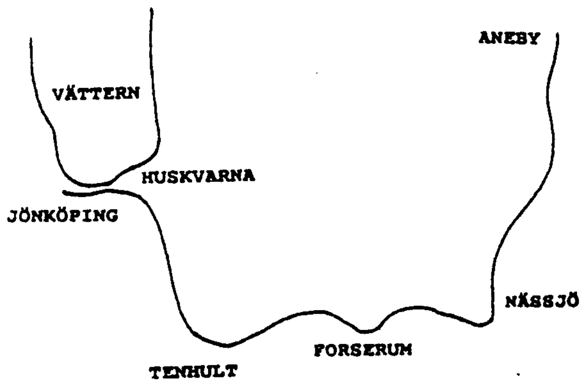


FIGURE 4:4 Jönköping 1987.

Test surveys were carried out in Jönköping in 1987. Here too, significant contradictions occur between ML (1981) and FL (1958.). Another reason for the test surveys was to try to get an idea of what effect geomagnetism has on the observations. Therefore, the surveys were planned along two survey lines; one in a north-south direction and the other in an east-west direction. The two lines co-incide both with the 2nd precise levelling (1958) and with the 3rd precise levelling (1981). The surveys covered 86 km and 83 sections. The terrain varied between wooded areas and farmland. About 75% of the roads were tarmac and the remainder were unmade roads.

5. PRODUCTION RESULTS

Production results from surveys carried out in the three areas are shown in table 5:1.

There is a difference in surveying methods between ML and MTL. Because of this, the "setting up of a station" has a different meaning in each case. Figure 5:1 and 5:2 illustrate the differences. In ML, the number of setups corresponds to the number of elevation differences observed. This does not apply to MTL. When using MTL, there is an additional difference in elevation for each section. Therefore, it is the total number of elevation differences observed that is shown in table 5:1, column 7.

In column 8, the average sight distances are given for each method. As the difference in distance between observations towards bench marks and observations between vehicles is so great when using MTL, two values are given. the first value (H_2 and H_3 in figure 5:2) refers to the distance when observing between vehicles. The other value (H_1 and H_4) refers to the distance when observing bench marks.

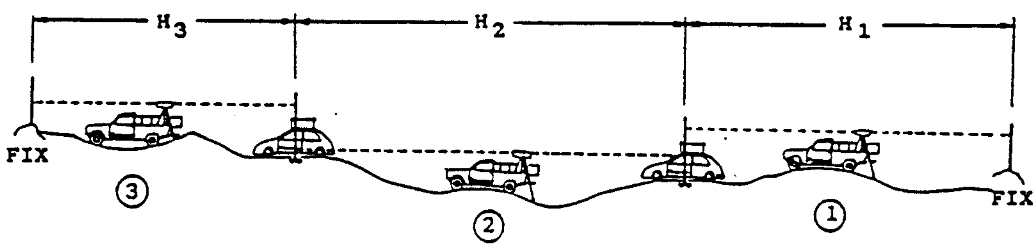


FIGURE 5:1 ML surveying procedure. The number of setups = the number of observed elevation differences.

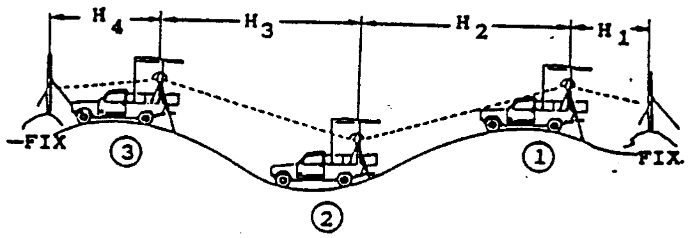


FIGURE 5:2 MTL surveying procedure. The number of elevation differences = the number of setups + 1.

In total (MTL + ML + FL), approximately 1500 km has been levelled. Converted to an eight hour working day, one hundred and fifty working days have been used by four people. A total of approximately 15,000 elevation differences have been observed.

PRODUKTION RESULTS

AREA	YEAR	METHOD	DIST. (KM)	NO OF SEC-TIONS	TIME (H)	*) NO OF SETUPS	**) MEAN SIGHT DIST. (M)	TIME/ SETUP (MIN)	KM/H	SETUPS/ KM
FALUN	1985	ML	42.2	48	26.0	640	33.0	2.44	1.62	15.2
	1985	MTL	36.6	40	22.9	174	284/20	7.90	1.60	4.8
SÄLEN	1986	ML	441.4	450	210.0	6004	36.8	2.10	2.10	13.6
	1986	MTL	479.8	478	252.8	2974	194/20	5.10	1.90	6.2
JÖNKÖPING	1958	FL	124.0	120	186.0	1320	47.0	8.45	0.67	10.6
	1981	ML	171.1	174	106.4	2548	33.6	2.51	1.61	14.9
	1987	MTL	190.2	190	116.4	1391	156/30	5.02	1.63	7.3
TOTAL		ML	654.7	672	342.4	9192	35.6	2.23	1.91	14.0
		MTL	706.6	708	392.1	4539	186/23	5.18	1.80	6.4

FL = Levelling on foot (the 2nd precise levelling)
ML = Motorized levelling (the 3rd precise levelling)
MTL = Motorized trigonometric levelling

*) In MTL the number of setups is calculated from the number of height differences measured.
**) In MTL two values are given; the first refers to the distance when observing between vehicles and the other refers to the distance when making bench mark ties

TABLE 5:1 Summary of survey statistics.

6. ACCURACY ANALYSIS

The analysis is subdivided into three sections:

* analysis of the internal accuracy of MTL and ML.

* analysis of MTL compared with ML.

* analysis of MTL and ML compared with other methods, for example, levelling on foot and other ML surveys.

The accuracy analysis was carried out in the following way:

* Different tests were carried out using elevation discrepancies for individual sections. These discrepancies were obtained from forward and reverse levelling and used to estimate the internal accuracy of a method. Discrepancies were also obtained by comparing mean values from different methods in order to compare one method with another. The following tests were carried out:

  + field test checking discrepancies against the rejection limit

  + test for any systematic trend in discrepancies

  + linear regression of the discrepancies in order to see which parameters are involved in any systematic effects that occur. The parameters tested were distance, square root of distance and the absolute value of the elevation differences

  + computation of the standard error of mean in order to check precision.

* Test of loop misclures.

* Net adjustment of levelling lines by least squares method including checking for blunders using a simplified variant of Baarda's "datasnooping" [3].

6.1 The internal accuracy of MTL and ML

MTL observations used in the analysis were uncorrected field data whereas ML observations had been corrected for Earth curvature, rod temperature and systematic errors in rod divisions.

For the field test of forward and reverse levelling of a single section, the rejection limit 2 L has been used, except in the MTL survey in Jönköping where the rejection limit 2.8 L was used. The rejection limit 2 L is empirically derived. By using this, approximately 5% re-levelling was experienced in the National Precise Levelling Programme currently in progress. The field test in the experiment, however, produced a high proportion of re-levelling, 8-21% with the rejection limit 2 L for both MTL and ML (see table 6:1). The high proportion of re-levelling for ML is perhaps due to the great height differences between the bench marks which in turn led to a large number of stations.

Area Method/year	Rej. limit	No of sect. No relev.	Tot.	Dist. (km)	No. > rej.limit	Standard err of mean
Falun ML 85	$2\sqrt{L}$	18 3 (16.7%)	21	21.1	4 (19.0%)	0.95 $mm/\sqrt{km}$
Falun MTL 85	$2\sqrt{L}$	18 1 (5.6%)	19	18.3	3 (15.8%)	0.70 $mm/\sqrt{km}$
Sälen ML 86	$2\sqrt{L}$	196 29 (14.7%)	225	220.7	34 (15.1%)	0.71 $mm/\sqrt{km}$
Sälen MTL 86	$2\sqrt{L}$	196 37 (18.9%)	233	233.9	49 (21.0%)	0.85 $mm/\sqrt{km}$
Jönköping ML 81	$2\sqrt{L}$	83 7 (8.4%)	90	93.5	8 (8.9%)	0.66 $mm/\sqrt{km}$
Jönköping MTL 87	$2.8\sqrt{L}$	83 5 (6.0%)	88	93.0	6 (6.8%)	0.76 $mm/\sqrt{km}$
Total ML	$2\sqrt{L}$	297 39 (13.1%)	336	335.3	46 (13.7%)	0.71 $mm/\sqrt{km}$
Total MTL	$2.8\sqrt{L}$ $2\sqrt{L}$	297 43 (14.5%)	340	345.2	31 (9.1%) 69 (20.1%)	0.82 $mm/\sqrt{km}$

Table 6:1 Summary of field tests and standard error of mean.

In the analysis of MTL, a number of other rejection limits were tried using the survey material from Sälen. The precision of the mean value was, for the Sälen material, 0.85 mm/ km which is equivalent to a standard error in one observation of 1.20 mm/ km. Using this standard error, new rejection limits were calculated for 5%, 10% and 20% risk levels. The new rejection limits correspond well with the rejection of observations (see table 6:2). In the MTL survey in Jönköping, the rejection limit of 2.8 L was used.

Standard err of observ.	Risk-level	Rejection limit	No of observ.	No of obs. > rej.limit
1.2 mm/$\sqrt{km}$	5%	3.33$\sqrt{L}$	233	14 (6.0%)
1.2 mm/$\sqrt{km}$	10%	2.80$\sqrt{L}$	233	25 (10.7%)
1.2 mm/$\sqrt{km}$	20%	2.17$\sqrt{L}$	233	46 (19.7%)

Table 6:2 Test of rejection limits using MTL observations in Sälen.

The analysis regarding systematic effects shows that these only occur in the discrepancies from the MTL survey in Falun and the ML survey in Sälen. A further examination using regression analysis shows that:

* there is a systematic trend of some significance occuring in the discrepancy with regard to the absolute value of the height difference from the MTL survey in Falun. The material is limited, however, with only 19 sections. The remaining observations, 321 sections, do not show any sign of systematic influence.

* there is a strong systematic trend in the discrepancies with regard to the length of the ML survey in Sälen (see figure 6:1). A satisfactory explanation has not been found for this.

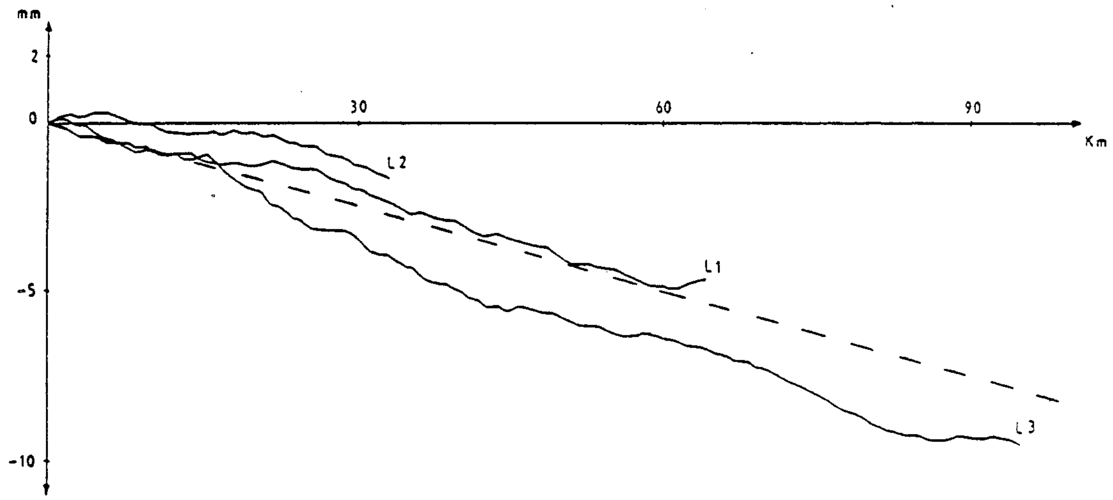
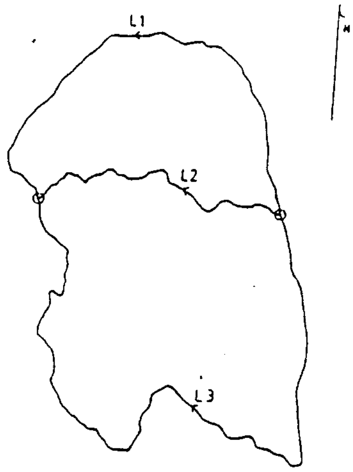


Figure 6:1 Graph showing the systematic errors for ML in Sälen. The solid line shows the accumulated discrepancy for each levelling line. The pecked line shows the linear regression y=cx; where y is the discrepancy in mm, x is the distance in km and c=0.83 mm/km.

Calculation of the standard error of mean shows that both methods produce a precision better than 1 mm/ km (see table 6:1).

Finally, a test of loop misclosure and net adjustment was carried out with the Sälen survey material. Both these tests still show that precision is better than 1 mm/ km (see table 6:3).



	L	ML 87	MTL 87
Misclosure =L2-L1	97.1 km	-3.40 mm	+7.20 mm
Misclosure =L3-L2	127.7 km	+5.05 mm	+5.86 mm
Misclosure =L3-L1	158.6 km	+1.65 mm	+13.06 mm
Estimated standard deviation obtained in net adjustment		0.35 mm/$\sqrt{km}$	0.75 mm/$\sqrt{km}$

Table 6:3 The table shows loop misclosures as well as results from the net adjustment of the Sälen surveys.

6.2 Analysis of MTL compared with ML

The rejection limit 2.8 L was used for comparative field tests regarding methods. This rejection limit was calculated using a standard error of 1.0 mm/ km for both methods and with a risk level of 5%. See table 6:4 for results of field test.

The search for a systematic effect in the discrepancies did not produce any significant results. Moreover, the standard error of mean was less than 0.71 mm/ km which is the standard error that will be obtained if both methods' mean value have a standard error of 1.0/ km. Finally, the accumulated discrepancies were calculated and plotted. The results are shown in figures 6:2-4.

Area	No of sections	Dist.	No > $2.8\sqrt{L}$	Standard err of mean
Falun MTL 85 - ML 85	18	17.6	0 (0.0%)	0.69 mm/$\sqrt{km}$
Sälen MTL 86 - ML 86	196	191.7	6 (3.1%)	0.59 mm/$\sqrt{km}$
Jönköping MTL 87 - ML 81	83	85.6	5 (6.0%)	0.69 mm/$\sqrt{km}$
Total MTL - ML	297	294.9	11 (3.7%)	0.63 mm/$\sqrt{km}$

Table 6:4 Results of field tests of discrepancies between the mean values of MTL and ML, as well as the standard error of mean.

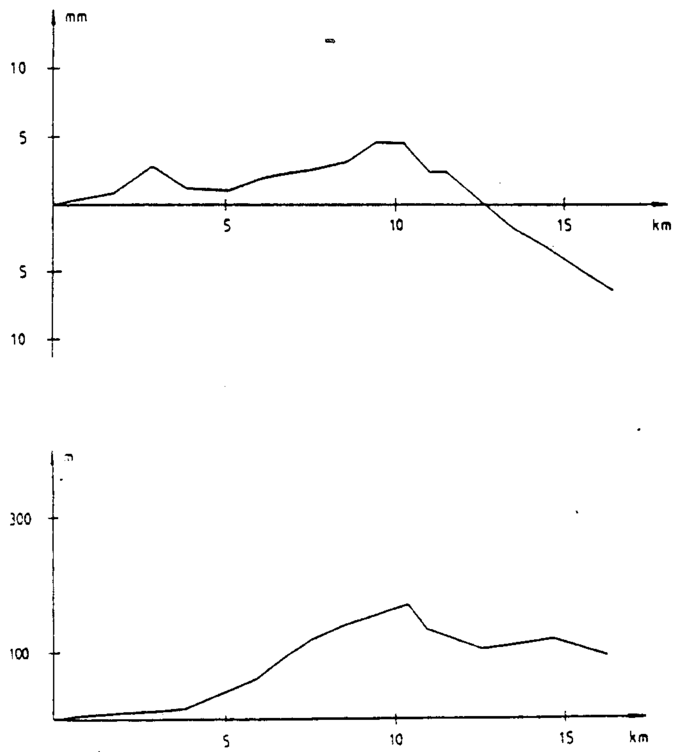


Figure 6:2 Accumulated discrepancies MTL-ML for the Falun survey and also the elevation profile.

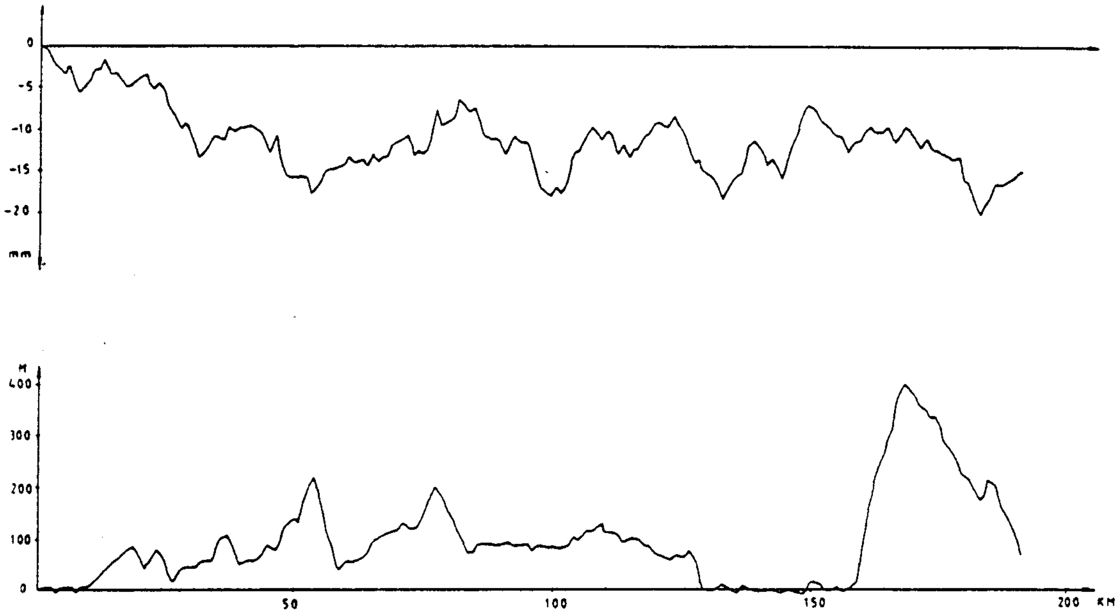


Figure 6:3 Accumulated discrepancies MTL-ML, for the Sälen survey and also the elevation profile.

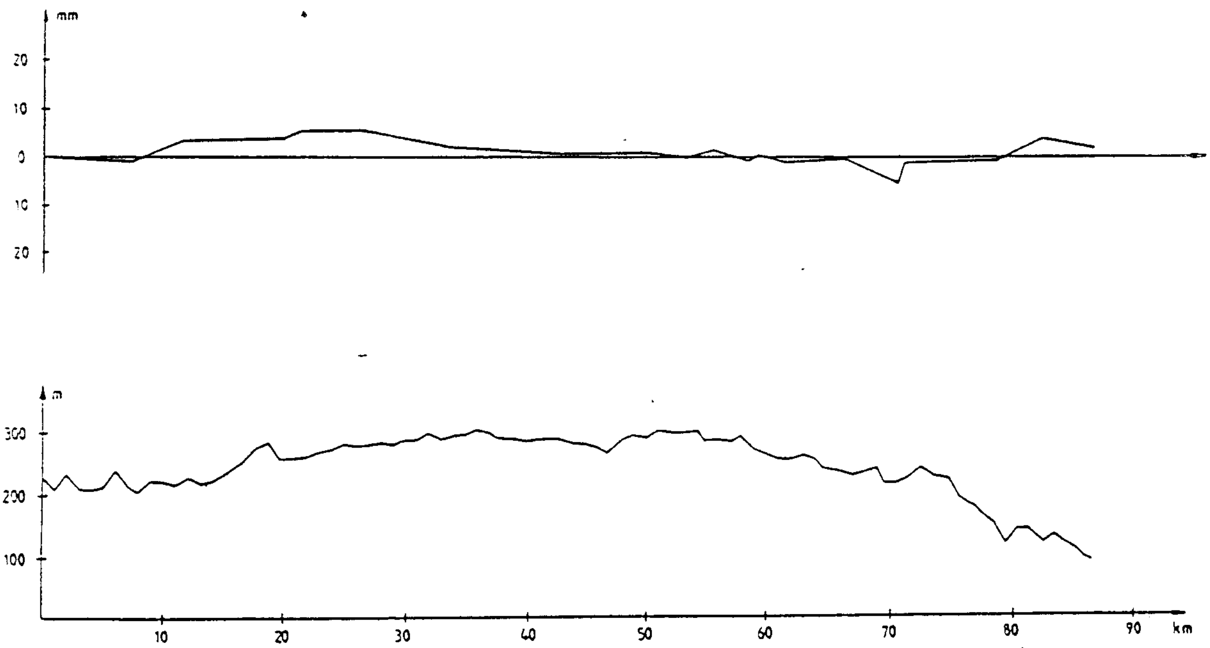


Figure 6:4 Accumulated discrepancies MTL-ML, for the Jönköping survey and also the elevation profile.

6.3 Analysis of MTL and ML compared with other surveys

The Falun levelling line has been surveyed on other occasions times using ML; in 1979 and 1987 (see table 6:5 and figure 6:5).

Area Method/Year	Rej. limit	No of sect. No relev.	Tot.	No > rej.limit	Standard err of mean
Falun ML 79	$2\sqrt{L}$	18 11 (16.7%)	29	17 (58.6%)	1.25 mm/$\sqrt{km}$
Falun ML 87	$2\sqrt{L}$	18 0 (0%)	18	0 (0%)	0.49 mm/$\sqrt{km}$
ML79-ML85	$2.8\sqrt{L}$	18 -	-	0 (0%)	0.50 mm/$\sqrt{km}$
ML87-ML85	$2.8\sqrt{L}$	18 -	-	1 (5.6%)	0.56 mm/$\sqrt{km}$
MTL85-ML85	$2.8\sqrt{L}$	18 -	-	0 (0%)	0.69 mm/$\sqrt{km}$

Table 6:5 Summary of field tests for ML79 and ML87 and between areas. Standard error of mean is also shown.

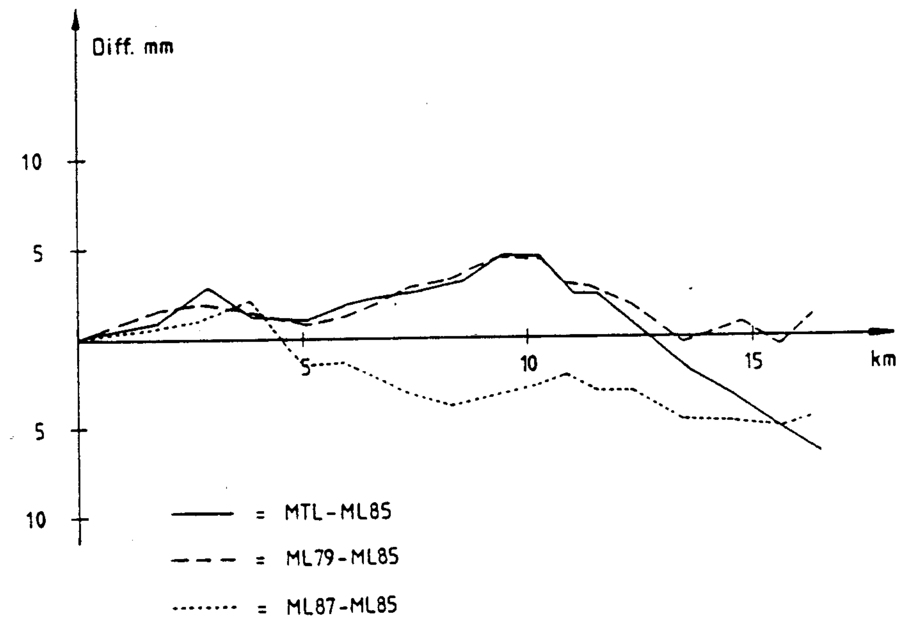


Figure 6:5 The accumulated discrepancies between MTL85-ML85, ML79-ML85 and ML87-ML85.

The Jönköping survey line is a precision line in the 2nd precise levelling programme and was surveyed by levelling on foot in 1958 (FL58). These measurements were corrected for Earth curvature, refraction and systematic errors in rod divisions. The Kukkamäki refraction model was used for refraction correction [2].

The analysis of the internal accuracy of FL58 shows that precision is high. No form of systematic effect can be found in the discrepancies between forward and reverse levelling. In a comparison of FL58 with ML85 and MTL85, a considerable systematic effect with regard to the absolute value of the height difference was obtained. Such a systematic effect can be explained by one or the other of the following: a bad refraction model or an unsatisfactory rod calibration. The correction for refraction was then removed and a somewhat better result was obtained but the systematic effect was still significant (see table 6:6 and figures 6:6-7).

Area Method/year	Rej. limit	No of sections	Dist. (km)	No > rej.limit	Standard err of mean
Jönköping ML 81	$2\sqrt{L}$	21	85.8	3 (14.3%)	0.68 $mm/\sqrt{km}$
Jönköping FL58	$2\sqrt{L}$	21	62.0	0 (0%)	0.29 $mm/\sqrt{km}$

Table 6:6 Result from the field test and the computed standard error of mean.

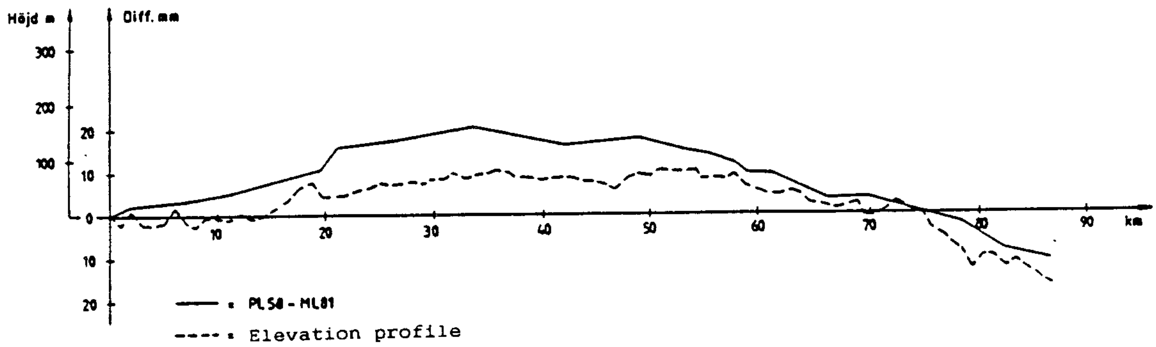


Figure 6:6 Graph showing the accumulated discrepancies between FL58-ML81 and also the elevation profile.

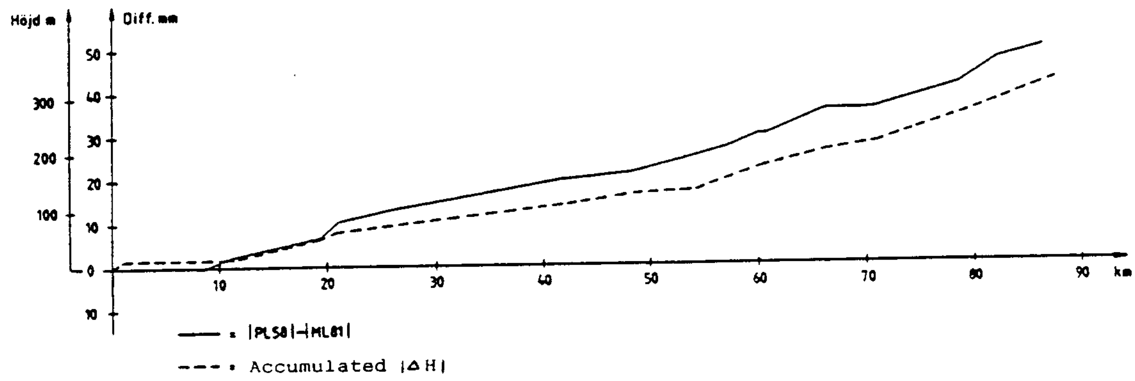


Figure 6:7 Graph showing the accumulated discrepancies between the absolute values of FL58 and ML87, as well as the accumulated absolute values of the height-differences. Linear regression with $y=cx$ gives $c=0.14$ mm/m; where y is the difference between the absolute value for FL and the absolute value for ML in mm, x is the absolute value of the height difference in m.

7. CONCLUSIONS

The experience we have gained from more than seven hundred kilometres of levelling observations using the MTL technique at various times of the year and in different areas can be summarised as follows:

1. The use of MTL and double-run levelling meet the requirements laid down for precise levelling (i.e. the standard error of mean is better than 1.0 mm/ km).

2. The results from single-run levelling using MTL show no systematic tendencies in contrast to the results from the ML survey where single observations quite clearly suffer from systematic effects (see also previous investigations [5].

3. Using MTL, the rejection limit for the discrepancy between two separate observations in opposite directions can be allowed to reach 2.8-3.0 L in the highest precision levelling.

4. MTL (Kern E2 and DM 503) and ML (Ni002) techniques both produce the same heights even when these results differ considerably from previous surveys, for example, using the standard FL method (Wild N3). The discrepancies between MTL and ML compared with the FL result show a systematic effect which is proportional to the observed elevation differences.

5. It is not possible to detect any effects of geomagnetism in the ML survey when using the Ni002 instrument irrespective of observation direction.

6. The production capacity (km/hour) of MTL (using three survey vehicles) is about the same as that for the ML technique - around 2 km/hour.

7. The cost of production (SEK/km) is, however, higher for the MTL technique. This is partly due to the high cost of investment and partly due to the topography of the Swedish landscape and vegetation which does not lend itself to long lines of sight in MTL (less than 200 meters). In addition, too much time is spent on each setup.

8. The MTL technique is far more advanced technologically and also more automated than ML which makes it more vulnerable in connection with fieldwork (difficult to find and remedy faults, especially electrical faults).

9. Furthermore, MTL requires experienced and well-trained personnel as everyone in the team has to carry out qualified surveys (this requirement is lower in ML). Personnel must also have the ability to follow well-defined survey routines in order to achieve the highest possible degree of accuracy.

10. The MTL technique has one advantage in that it can be used for 3D surveys in which case it is known as "MXYZ". The result shows very high quality and indicates that the method could be advantageous in towns etc.

11. The ML technique, which at present is the most competitive of the precise levelling methods (all factors considered), would benefit from being more "automated", for example, by incorporating automatic reading facilities in the instruments or rods.

We believe that the MTL technique used in mountain regions and very hilly terrain with open landscape will in economic terms, compete with the ML technique, even though in Sweden surveying in these areas is somewhat limited.

To summarise, we can say that ML and MTL are two very efficient precise levelling techniques which will take over from the standard precise levelling on foot method. Moreover, they also have the potential for improvement.

8. REFERENCES

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