

Current Research and Development at the Nummela Standard Baseline

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Key words: length metrology, geodetic baseline, Nummela, Väisälä comparator, traceability.

SUMMARY

The 60-year-old Nummela Standard Baseline is a unique length standard in geodetic metrology. This was verified again in the latest remeasurement with the Väisälä (white light) interference comparator in autumn 2005. In this presentation we briefly present the newest results with some analysis and advances in the traceability chain. Present-day utilization of the baseline is illustrated with brief descriptions of recent and topical research and development projects. As a National Standards Laboratory the Finnish Geodetic Institute is a participant in the Mutual Recognition Arrangement (MRA) by the CIPM. All the activities meet the requirements of the ISO/IEC 17025:2005 and ISO 9001 quality standards.

Since the beginning of interference measurements in 1947, the length of the 864-m-long baseline has changed less than 0.6 mm, and standard uncertainty has been smaller than 0.1 ppm. This enables reliable calibrations of the most precise electronic distance measurement (EDM) instruments in field conditions and traceable scale transfers. New working premises, completed in year 2004, and sheltering constructions around the observation pillars have greatly improved working conditions at the baseline.

A quartz gauge system is used to determine traceability to the definition of the metre. Latest absolute calibrations for 1-metre-long quartz gauges have been performed using gauge block interferometers of PTB, Braunschweig, and MIKES, Helsinki. The system is maintained in the Tuorla Observatory of University of Turku with regular relative interferometric comparisons. In Nummela we use the quartz gauge no. VIII, the length of which is known from the absolute calibrations and comparisons with about ± 70 nm uncertainty ($k=2$). With the Väisälä interference comparator we multiply this length into the distances between observing pillars, and, after projecting, into the distances between underground markers. The underground baseline preserves the attained high accuracy, which we use to calibrate the most precise surveying instruments.

Results of customary EDM calibrations are used in various geodetic and metrological works. The scale can be traceably transferred to other baselines or test fields, which are used e.g. in deformation studies or in small geodynamical monitoring networks. In 2006 we are waiting for the first measurements with the new instruments based on the new frequency comb technology. Official international comparisons in geodetic metrology are also coming true.

YHTEENVETO – Nummelan Normaali-perusviiva tänään

Avainsanat: pituusmetrologia, perusviiva, Nummela, Väisälä-komparaattori, jäljitettävyyden.

Mittasimme Nummelan Normaali-perusviivan syksyllä 2005 Väisälä-komparaattorilla 432 metriin asti. Mittaus oli vuonna 1947 alkaneessa sarjassa 14:s. Tulokset osoittavat, että viiva on yhä kansainvälisesti ainutlaatuinen mittanormaali pituusmetrologiassa. Tässä artikkelissa esittelemme uusimmat tulokset ja vertailun aiempiin mittauksiin sekä koko jäljitettävyyden ketjun metrin määritelmästä käytännön kenttämittauksiin. Muutaman esimerkin avulla esittelemme viivan nykyistä käyttöä kalibroinneissa ja vertailumittauksissa sekä mittakaavan siirroissa muille perusviivoille, testikentille ja seurantaverkkoihin. Geodeettinen laitos on kahden suureen, pituuden ja putoamiskiihtyvyyden, kansallinen mittanormaali-laboratorio ja mukana kansainvälisessä metrologia-alan laitosten keskinäisessä ekvivalenssisopimuksessa (CIPM MRA). Toimintamme ohjaa ISO/IEC 17025:2005 ja ISO 9001 -standardien mukainen laadunhallintajärjestelmä.

Vuodesta 1947 perusviivan koko 864 m:n pituus on vaihdellut alle 0,6 mm ja standardi-epävarmuus on ollut alle 0,1 ppm. Tämä riittää kaikkein tarkimpien elektronisten etäisyysmittareiden kalibrointiin ja luotettaviin, jäljitettäviin mittakaavan siirtomittauksiin. Kalibroinnit voidaan tehdä kenttäoloissa kuten sovellusmittauksetkin, ja menetelmä on taajuuskalibroinneista riippumaton. Vuonna 2004 valmistuneet uudet työtilat ja pilarien kattaminen ja aitaaminen ovat suuresti parantaneet työoloja Nummelassa. Havaintopilarien kunnostus jatkuu.

Mittausten jäljitettävyyden metrin määritelmään tulee kvartsimetri-järjestelmän kautta. Järjestelmää ylläpitävät Tuorlan observatoriossa säännöllisin interferometrisin vertailumittauksin Turun yliopisto ja (vuodesta 2005) Geodeettinen laitos. Metrin mittausten kvartsi-sauvojen viimeisimmät absoluuttikalibroinnit on tehty Saksan PTB:ssä ja Suomen MIKESissä. Nummelan mittauksissa käytämme kvartsimetriä n:o VIII, jonka pituus tunnetaan absoluuttikalibroinneista ja vertailumittauksista noin 0,000 000 035 m eli 35 nm standardi-epävarmuudella. Valkoisen valon interferometriaan perustuvalla Väisälä-komparaattorilla tämä pituus moninkertaistetaan peilipintojen väliseksi etäisyydeksi havaintopilareilla ja nämä projisoidaan edelleen maanalaisten kiintopisteiden väliseksi etäisyydeksi.

Perusviivalla kalibroidaan vain tarkimpia elektronisia etäisyysmittareita. Näitä käytetään mm. mittakaavan siirtomittauksissa tavallisten maanmittauskojeiden kalibointiperusviivoja ja testikenttiä varten. Nummelan mittakaava on näin siirretty 10 maahan viimeisten 10 vuoden aikana. Paikallisen geodynamiikan tutkimisessa tarkkuusmittauksia käytetään mm. Olkiluodon ja Metsähovin seurantaverkoissa. Viime vuosien kansainväliset vertailumittaukset liittyvät tavanomaisen metrologiayhteistyön ohella uusien mittauskojeiden ja -menetelmien kehittelyyn.

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1. BACKGROUND

Length metrology has been an essential part of activities at the Finnish Geodetic Institute (FGI) since the foundation of the institute in 1918. In 1933 a new baseline was established in Nummela, 45 km NW of Helsinki. The design was fitted for comparisons of invar wires, 36 x 24 m = 864 m. Later the baseline was equipped for the Väisälä interference comparator, and since the first interference measurements in 1947 it has been called the Nummela Standard Baseline. With 14 interference measurements in 1947–2005 it has remained a valuable national and international length standard with verified traceability and extreme stability.

Unlike laser interferometers, the Väisälä interference comparator uses white light, which makes it usable in field conditions, and opens up an independent alternative to other calibration methods. Importance of Väisälä standard baselines was acknowledged already in 1951 in the IAG General Assembly, which recommended such measurements in different countries. Until 1970s the baselines were mainly used for calibration of invar wires and EDM instruments for nation-wide triangulation. Later they have served in scale transfers and calibrations for local measurements, and also in instrument testing and product development. Today the Nummela Standard Baseline is one of the few treasured Väisälä baselines in the world. New interference measurements are performed every few years.

Recently we have greatly improved our working conditions in Nummela. In 2004 we replaced the 70-years-old dilapidated storehouses with a new office building. The underground benchmark pillars from 1933 and the observation pillars from 1946 were sheltered with roofs and wire-netting fences, and a part of the area was fenced (Fig. 1–3). Constructions and interfaces on observation pillars will be improved in the next reconditioning phase in near future.

The FGI is the National Standards Laboratory of length (geodetic measurements) and acceleration of free fall (i.e. gravimetry), and a participant in the Mutual Recognition Arrangement (CIPM MRA; see <http://www.bipm.org/en/cipm-mra/>) for national measurement standards and for calibration and measurement certificates issued by national metrology institutes. All the activities meet the requirements of the quality standards ISO/IEC 17025:2005 (General requirements for the competence of testing and calibration laboratories) and ISO 9001:2000 (Quality management systems – Requirements). The quality system is described in the quality manual.



Fig. 1. The new main building.



Fig. 2. Väisälä comparator house.



Fig. 3. The shelter for observation pillar and underground marker at 864 m.

2. TRACEABILITY

The length unit, metre, is realized e.g. in Finland in the Centre for Metrology and Accreditation (MIKES) with iodine stabilized He-Ne or Nd:YAG lasers. These lasers are utilized in interferometers to determine traceable lengths for gauge blocks, in our case for quartz metres. At Nummela we transfer traceability from these to geodetic measurement instruments.

2.1 Absolute Calibrations of Quartz Metres

In 2000, MIKES developed a method for absolute calibrations of quartz metres. An application of interferometer for long gauge blocks was used; the method is described in Lassila et al. (2003). Until 1995 we had used comparable services of the PTB and BIPM. In 2000, lengths of four quartz metres (including no. VIII, that is used in Nummela) were determined with ± 72 nm uncertainty (extended, $k=2$). The results and error estimates go well together with the previous works in the PTB and Tuorla Observatory.

2.2 Relative Comparisons of Quartz Metres

The quartz gauge system has been maintained with interferometric comparisons in the University of Turku (UTu) since 1933 (Kukkamäki 1933), since 1952 in the bedrock tunnel laboratory in Tuorla Observatory. The latest short description of the system is by Niemi (2003). In 2005 two experts of the FGI were trained to take care of the system in the future. Precision of the comparisons is up to a few nm.

We use a comparator box with two planar glasses, two Cd spectral lamps, shading plates and camera and control units, all these in a temperature-controlled cave room. Three quartz metres are placed between the exactly parallel glass plates (Fig. 4), a gap (< 1 mm) is left at both ends. The quartz metre in the middle is to be measured, and the other two are used to control the stability of the glass plates. At both ends, prisms split the beams from the light sources in four colours. Reflections from the glass surface and the quartz metre end produce interference fringes, which are photographed. Gaps between the metres and glass plates are determined by measuring the photographed fringes with a computer program.

The distance between the glass plates is first determined using a quartz metre of known length in the middle. Then we replace it with another quartz metre, the length of which we get by subtracting the gap widths. We utilize not only results of absolute calibrations, but use always first (and last, to get a closing error) a transfer standard, the principal normal quartz metre no. 29. Numerous comparisons and links to absolute calibrations have made this quartz metre the backbone of the quartz gauge system (now BTM00, Braunschweig–Tuorla–MIKES 2000).

2.3 Väisälä Interference Comparator

The principle of the historical Väisälä (white light) interference comparator is well known and reported in several publications and not presented here in detail (see e.g. Väisälä 1923,

Kukkamäki 1969 and Jokela and Poutanen 1998; for recent projects with applications to high precision EDM see also Jokela et al. 2000 and 2001). In Nummela, we multiply the length of the quartz metre no. VIII, 1.000 151 32 m, to lengths between mirror surfaces on observation pillars, up to $1\text{ m} \times 6 \times 4 \times 3 \times 2 \times 2 \times 2 = 864\text{ m}$ (Fig. 6–8). Since 1947, 12 such measurements have been made, and two more times just to 432 m, because of continuously unfavourable weather conditions.

To preserve the traceable lengths, projection measurements from the observation pillars to more stable underground benchmarks are needed before and after (and during) the interference measurements. The underground pillar line runs parallel with the observation pillar line, next to it. The projections are based on precise angle measurements between mirrors and underground markers and on transfer readings between mirror surfaces and transferring bars. Transfer readings determine the distance between the (fixed) transferring bar and (adjustable) mirror surface with 0.001 mm accuracy (Fig. 8), and the underground markers we reach at 0.01 mm accuracy with mechanical plumbing (Fig. 5). In calibrations reverse projections between the underground markers and forced-centring plates on the pillars are needed.

2.4 Calibration of EDM Instruments

Following the traceability chain, we now end to a standard baseline for use in high precision EDM calibrations. The method is independent on the more common frequency calibrations. For estimation of total error, contribution of every stage in the traceability chain must be estimated and finally summarized to an uncertainty estimate, which is presented as a part of the results. Onwards, only a few types of EDM instruments can be used as transfer standards; many Kern Mekometer ME5000s are still capable, some Leica models can be considered (Fig. 9–10). During the last twenty years tasks have changed from the support of practical surveying to more scientific applications for metrology, geodesy and geodynamics; calibrations for triangulation measurements ended, and instrument tests for local measurements are performed elsewhere.

3. INTERFERENCE OBSERVATIONS

Interference observations with the Väisälä comparator require extremely stable temperature conditions for lengths of a few hundred metres and longer. Otherwise it is not possible to control the course of reflecting light beams and to adjust the mirrors and compensators with the required 0.001 mm accuracy to find the interference fringes. In Nummela this is usually possible in a few autumn nights. In 2005, seven successful interference measurements to 432 m were performed between October 19th and November 13th, after several weeks preparations and waiting for favourable weather conditions. A few attempts for the 864-m-interference were made, but the completely cloudy nights needed for this were totally missing during September–November. We hope to be luckier in the next measurements in the near future. For the measurement procedure in general and details of computation see e.g. Jokela et al. (1998, 2000, 2001); a full listing of the 7 interference measurements and 19 projections in 2005 will be published later.

3.1 Results 1947–2005

A summary of new and old results is given in Table 1. Length of the quartz metre in BTM00 system was determined in comparisons in the Tuorla Observatory in April and December, 2005.

It often takes several years before new benchmarks settle in the soil. Omitting this, the baseline is extremely stable, and the repeatability of measurements is excellent. For both 432 m and 864 m, variation of length has been smaller than 0.6 mm since 1947.

Table 1. The lengths of the Nummela Standard Baseline sections in 1947–2005 with standard uncertainties.

Epoch	0 – 24 mm + 24 m	0 – 72 mm + 72 m	0 – 216 mm + 216 m	0 – 432 mm + 432 m	0 – 864 mm + 864 m
1947.7	—	—	—	95.46 ±0.04	122.78 ±0.07
1952.8	—	—	—	95.39 ±0.05	122.47 ±0.08
1955.4	—	—	—	95.31 ±0.05	122.41 ±0.09
1958.8	—	—	—	95.19 ±0.04	122.25 ±0.08
1961.8	—	—	—	95.21 ±0.04	122.33 ±0.08
1966.8	—	—	—	95.16 ±0.04	122.31 ±0.06
1968.8	—	—	—	95.18 ±0.04	122.37 ±0.07
1975.9	—	—	—	94.94 ±0.04	122.33 ±0.07
1977.8	33.28 ±0.02	15.78 ±0.02	54.31 ±0.02	95.10 ±0.05	122.70 ±0.08
1983.8	33.50 ±0.02	15.16 ±0.02	53.66 ±0.04	95.03 ±0.06	—
1984.8	33.29 ±0.03	15.01 ±0.03	53.58 ±0.05	94.93 ±0.06	122.40 ±0.09
1991.8	33.36 ±0.04	14.88 ±0.04	53.24 ±0.06	95.02 ±0.05	122.32 ±0.08
1996.9	33.41 ±0.03	14.87 ±0.04	53.21 ±0.04	95.23 ±0.04	122.75 ±0.07
2005.8	33.23 ±0.04	14.98 ±0.04	53.20 ±0.04	95.36 ±0.05	—

3.2 Uncertainty of Measurement

To meet better the requirements of new metrological directions in estimation of measurement uncertainty, we have reassessed the error budgets of latest measurements. Influences of some error sources were increased (mirror coating thicknesses, some projections), and some were decreased (quartz metre length, some projections). As expected, this didn't change the final results significantly, and the entire time series in Table 1 is consistent with each other.

The main error source has always been the projections between the mirrors on observations pillars and underground benchmarks. Refraction is not a problem: If temperature is not stable, we cannot observe, and when we observe, absolute value of refraction correction is not needed. The small relative correction we determine from readings of 29 thermometers along the baseline.



Fig. 4. Comparison of quartz gauges.



Fig. 5. Reaching for an underground marker at 0.01-mm-level by mechanical plumbing.

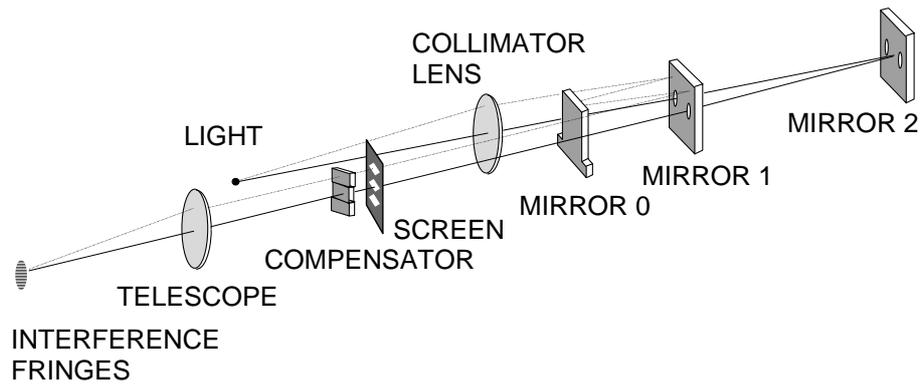


Fig. 6. Principle of the Väisälä comparator.



Fig. 7. Working with the Väisälä comparator.

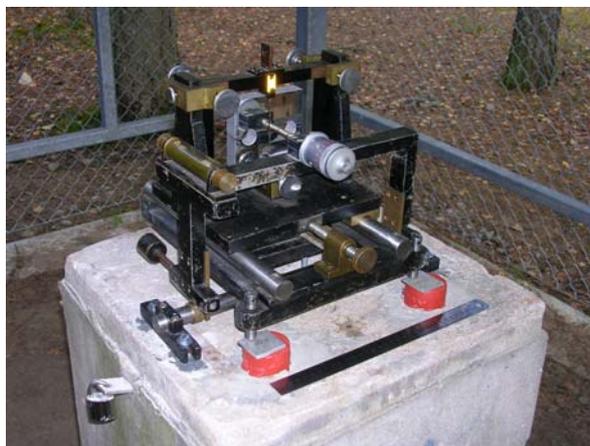


Fig. 8. Transferring device adjusted at a Väisälä comparator mirror equipment.



Fig. 9. Calibration of a tacheometer.



Fig. 10. Measuring a calibration baseline and test field in Lithuania.



Fig. 11. Measurements at the NMIJ/AIST baseline in Tsukuba, Japan.

4. USE OF THE BASELINE

4.1 Scale Transfer to other Baselines and Test Fields

During ten last years we have been co-operating in metrological measurement projects in ten countries. These include standard and calibration baseline measurements performed with the instruments of the FGI and the Helsinki University of Technology (HUT; Finland 75 m and 840 m, China 1 488 m, Hungary 432 m, Estonia 1 728 m, Lithuania 1 320 m + test field; Fig. 10), scale transfers performed by other institutes and instruments (Hungary 864 m, Taiwan, Norway, Kosovo), and co-operation at the baselines of other NMIs (Japan 96 m, Korea 280 m; Fig. 11).

Laborious standard baseline measurements are performed with the Väisälä interference comparator. Calibrations of the best available EDM instruments often follow immediately, and the baseline is extended to longer lengths with them. Without the comparator the scale can be traceably transferred by using the Nummela Standard Baseline as a length standard and calibrating the transfer instruments there before and after measurements at another baseline.

4.2 Local Geodynamical Research

To investigate scale errors of GPS solutions a 511-m EDM baseline was established in the GPS control network (Fig. 12) around the Olkiluoto nuclear power plant in 2002. The scale is transferred there from Nummela with the Kern Mekometer ME5000 of the HUT (Fig. 13). GPS and EDM observations are performed twice a year simultaneously. In the eight measurements so far, EDM distance is always shorter than the GPS result from same campaign (Fig. 14), indicating over 1 ppm systematic scale difference. Another feature is that the shapes of the short times series are quite similar. The reasons are still unknown, and interesting investigations are continuing. Results are published in Working Report series of Posiva; a recent summary was given by Ollikainen and Ahola (2006).

Geodetic observation methods at the Metsähovi research station of the FGI include e.g. VLBI, SLR, DORIS, GPS and GLONASS measurements, absolute and superconducting gravimetry and seismometry. To link the reference points with each other and to global reference frames, repeated high precision control measurements are needed. We use precision tacheometry and precise levelling to determine relative positions, and GPS measurements for orientation of the local control network. We have measured the control network (Fig. 15) thoroughly in 1997 and 2004, supplemented by numerous smaller measurements. In many respects we have obtained the expected one-millimetre accuracy, and proved the network stable. Monitoring and maintenance will continue. Tested and calibrated instruments are essential in this, and regular use of Nummela Standard Baseline is a standard routine. A report on the control measurements is in preparation (Jokela and Häkli 2006).

Another topical research subject in Metsähovi is the precise levelling test field (Fig. 16). A few years of frequently repeated levellings unexpectedly showed obvious seasonal variation of up to several mm in height differences between benchmarks in bedrock. The first results

are reported in Lehmuskoski et al. (2003). With our tacheometers, regularly tested in Nummela, we have measured possible related horizontal deformations. Sub-millimetre repeatability has been obtained, but with no clear evidence of horizontal movement.

4.3 International Comparisons

Bilateral comparisons of EDM instruments between the National Metrology Institute of Japan / National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) and the FGI were started in 2003 in Tsukuba, Japan. One instrument of the NMIJ/AIST and two of the Finnish Geodetic Institute (FGI) were tested in a 310-m optical tunnel. A 96-m laser interferometer baseline was used to analyze scale corrections and an adjacent 7-point baseline for additive constants. In addition to testing some of the most common precise surveying instruments, the work provides possibility to compare calibration services in two completely different operational environments (indoor laboratory vs. field conditions in Nummela, laser interferometer system vs. Väisälä baseline as a measurement standard). Results have not yet been published, but a draft programme for a more comprehensive comparison already in 2006 in South Korea has been prepared, now guided by the Asia Pacific Metrology Programme (APMP).

5. FUTURE

We plan to perform the next interference observations within a couple of years. Scale transfers to other geodetic baselines and test fields will continue, as well as applications in small high precision monitoring networks for geodynamical research. Launch of official international comparisons and development of new EDM instruments will bring new challenges. First instruments based on the new frequency comb technology are soon available. Most apparently the Nummela Standard Baseline will remain as a world-class measurement standard and stay in frequent use.

ACKNOWLEDGEMENTS

We thank the considerable number of people in the FGI, HUT and UTu, who greatly contributed to the successful practical execution of the measurements in 2005: Joel Ahola, Matti Christersson, Katri Koistinen, Hannu Koivula, Janne Kovanen, Kaisa Laatikainen, Mikko Moisander, Aimo Niemi, Henriikki Nordman, Markku Poutanen, Jyrki Puupponen, Paavo Rouhiainen, Veli-Matti Salminen, Maaria Tervo and Jani Uusitalo.

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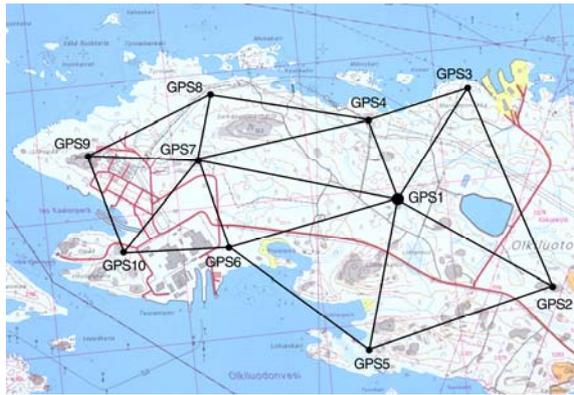


Fig. 12. A regularly calibrated EDM instrument (see example in Fig. 13) is used to control the scale of a vector in the GPS monitoring network at Olkiluoto nuclear power plant; see Fig. 14. (Figure by Joel Ahola).

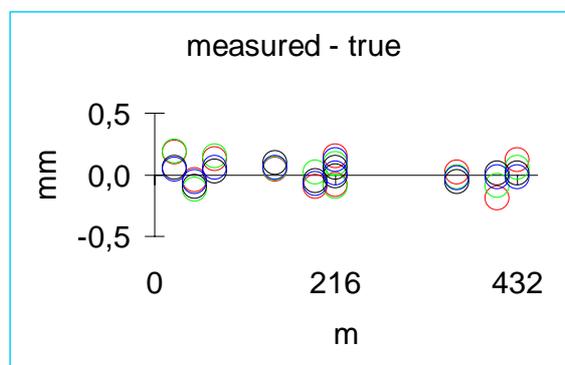


Fig. 13. Example of calibration of high precision EDM instrument. Results of four calibrations (4 x 2 x 10 measured distances) in Nummela in May 2006 show that the scale of the ME5000 of the HUT is greatly compatible with the scale of the baseline (true distances).

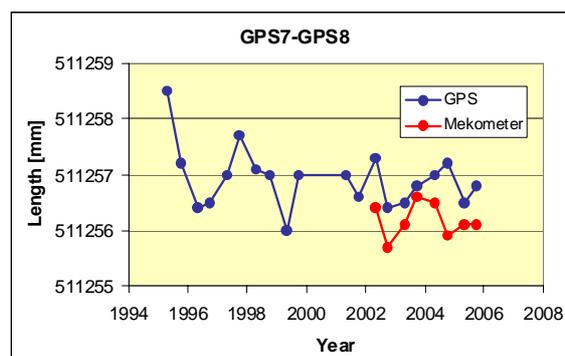


Fig. 14. Scale difference between GPS measurements and high precision EDM at Olkiluoto (Figure by Joel Ahola).

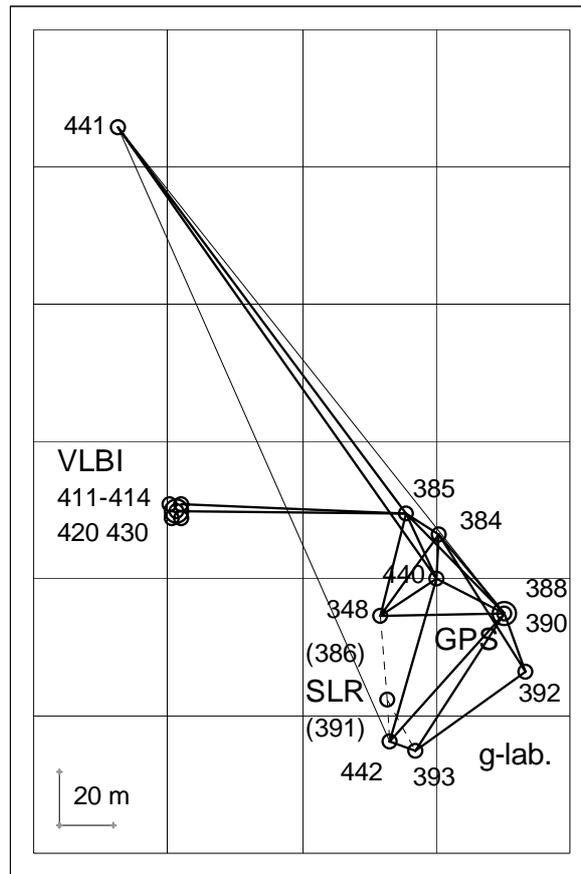


Fig. 15. Control network connecting the geodetic observation sites at Metsähovi.



Fig. 16. Metsähovi precise levelling test field.

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