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REVIEW OF THE GPS DEFORMATION MONITORING STUDIES

commissioned by Posiva Oy on the Olkiluoto, Kivetty and Romuvaara sites, 1994–2000

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Abstract

This report reviews the work done by scientists from the Finnish Geodetic Institute at the three sites Olkiluoto, Kivetty and Romuvaara over the years 1994–2000, with a view to detecting and measuring possible local crustal movements by means of geodetic GPS. The work, which consisted of measurements, computations and analysis, was reported in seven technical reports of Posiva Oy.

Reviewed was also the work related to the three permanent stations established in these three sites, which have operated as part of the twelve-station national FinnRef network.

The conclusion was that on the whole, the work has been performed professionally using state of the art equipment, measurement and analysis techniques by competent and experienced personnel.

A number of suggestions for improvement and future work are given, mainly concerning the way the modelling of atmospheric propagation effects was done and how that affects the scale of the network computation, a proposal for monitoring the absolute scale, as well as remarks concerning the regular re-measurement of reserve marker ties, and the importance of continuing monitoring for a full solar activity cycle. The importance of interdisciplinarity is stressed.

This review report is an outcome of the Bedrock Movements Investigations Group which supports STUK's regulatory activities related to confirming site investigations at Olkiluoto.

Contents

1 Introduction

During the period 1994–2000, a long series of geodetic measurements mostly using GPS was performed in the areas of Olkiluoto, Kivetty and Romuvaara that were tentatively proposed for final underground deposition of nuclear waste from the Finnish nuclear power stations. The objective of these measurements was to obtain an insight into the likelihood and possible magnitude of intra-crustal tectonic movements, which might have relevance to the safe containment of active substances in such a repository, and how it should be constructed to that aim.

It is of course understood that geodesy is only one discipline that can be used to address these issues. Obviously there are limitations in coverage and temporal duration in the measurements concerned that limit the nature of the conclusions that can be drawn from them. A thoroughly interdisciplinary approach involving all of geophysics including seismology, as well as the science of extreme events, is called for.

The work performed at the three sites, and the following processing and analysis, is described in the seven following technical reports:
Chen and Kakkuri (1995),
Chen and Kakkuri (1996),
Chen and Kakkuri (1997),
Chen and Kakkuri (1998),
Ollikainen and Kakkuri (1999),
Ollikainen and Kakkuri (2000), and
Ollikainen and Kakkuri (2001).

2 Measurement instruments and techniques

2.1
The GPS constellation and signals

From the beginning of the measurements in 1994 onward, there has been a complete GPS constellation of 24 satellites evenly spread around the globe, allowing measurement 24 hours a day. There have however been the following developments:

- Receiver technology has developed enormously, like all other information technology.
- Solar activity, which was on the downturn from the previous maximum around 1990, started climbing again towards the next maximum around 2000.
- On May 1, 2000, President Clinton ordered Selective Availability (SA) to be switched off

2.2
Receivers and antennas

Receivers used in the presently reviewed work were Ashtech receivers. Antennas were, from early 1996 onward, so-called Dorne-Margolin choke ring antennas. These are specially designed to minimize the impact of *multipath*, the effect of reections of the ground and nearby objects. A wise choice. Before that, Ashtech Geodetic antennas were used, a circumstance to take into account if one wishes to judge these early results.

On the nationwide FinnRef™ network, Ashtechs and Dorne-Margolin antennas are used as well. The antennas are mounted on most locations on steel grid masts; on the Olkiluoto, Kivetty and Romuvaara sites, however, carefully designed concrete pillars are employed, to further minimize the possible impact of thermal expansion and contraction with ambient temperature.

2.3
The Earth atmosphere

2.3.1 General

The areas of study, Olkiluoto, Kivetty and Romuvaara, are only several kilometres in diameter, so there are no measurement vectors within the areas longer than that. This means in general that the effects of the Earth atmosphere, both the neutral (“troposphere”) and the dispersive (ionosphere) refractive propagation effects, will be almost identical on both ends of a vector, and nearly cancel out in the determination of that vector.

However, when one strives for the greatest accuracy and repeatibility, on should take both into account anyway, as was done.

2.3.2 Ionosphere

When the series of GPS measurements started, the Sun was around a minimum in its eleven-year cycle of magnetic activity (“sunspot cycle”). As a result, the ionosphere was quiet and stable, meaning that ionospheric refraction, an important effect to be accounted for in GPS measurements, was small and behaving smoothly, both in location and in time. Measurements obtained under such conditions are easy to process by any suitable software, and produce good results.

Toward the end of the measurement series, solar activity increased, making ionospheric refraction a larger, more variable, and harder to model and predict quantity. Measurements processed under such conditions tend to produce poorer results, greater numbers of measurements will have to be discarded as being too contaminated, and during solar eruptions, which send ionizing radiation and particle streams towards the Earth, no useful measurement data at all may be produced, while outdoors one may enjoy the Northern Lights.

Normally in an area of the size considered here, one would perhaps not take the refractive effect of the ionosphere into account at all, or would do so by using the “ionosphere-free” linear combination of the two observables L_1 and L_2 obtained on different frequencies, exploiting the dispersive property of ionospheric refraction to eliminate it altogether from the resulting synthetic observable. However, for this work, this expedient choice was found not to be good enough, as it increases the noise level in this synthetic observable by a factor 3.

For this reason, the observations at L_1 and L_2 were used separately, correcting each for ionospheric path length effect using a predetermined model of the ionosphere, describing the density of the ionospheric refractive medium (TEC, Total Electron Content) as a function of both position and time). Such a model is a Taylor expansion with respect to latitude and longitude difference with the Sun, cf. Beutler et al. (2001) p. 208. In this case, the data from the permanent station at each site was used for determining the coeffcients of the model, as this station (which collects data around the clock) could be trusted to be in operation not only during, but before and after the local campaigns as well.

2.3.3 Troposphere

In small areas with little height variation it is possible to assume that the thickness of the neutral atmosphere, or “troposphere” in the jargon of GPS processors, is constant and thus nearly the same above the end points of every vector. However, this simple approach was not used here. Instead, a “tropospheric zenith delay parameter” was chosen for each station except GPS1, the base station used. Such a parameter TZD describes the total along-line-of-sight refraction as $TZD / \cos z$, where the cosine describes the geometric path lengthening with increasing zenith distance angle z, as the satellite stands lower and lower in the sky.

It is customary, when estimating tropospheric delay parameters in a small area, to fix the tropospheric delay to that of a standard atmospheric model for one chosen station, and solve for the others as free parameters, which will be time dependent for longer sessions.

2.4
Multipath

A major problem with highly precise GPS measurements is that of *multipath*, or interference of reflected radio waves with the directly received wave. Precise geodetic GPS uses measurements of the *phase* of the carrier wave (more precisely, of the difference in phase between waves received from pairs of satellites), which has a wavelength of either 21 or 19 cm. Interference by reflected waves (which have travelled along a different path and thus will have a quite different phase upon arrival at the antenna) can spoil these phase measurements.

In the design of the GPS system, this problem was foreseen and has been taken into account by circularly polarizing the radio beams emanating from the satellites. The direction of polarization is right-hand. Upon reflection, the direction changes to left-hand, and GPS antennas are designed to reject signal having this wrong polarization direction. This does not help against twice reflected waves, however.

For an antenna at 2 m above the reflective ground surface, the effect on the measured phase will typically vary in a quasi-periodic way with satellite elevation, as the ratio between wavelength and antenna height is ~ 10. One way to diminish the impact of multipath is thus, observing for so long a time span that these oscillations have a chance of canceling themselves out approximately.

The GPS constellation is built in such a way, that after 23^h56^m (one sidereal day) all satellites have completed two orbits and are again in the same positions in the local sky, having the same azimuths and elevations. This means that also multipath effects will repeat themselves from then onward, and further lengthening of the session time will not lead to further improvement from the multipath viewpoint.

The measurements at the three local sites generally did not cover an integral number of sidereal days, but shorter sessions were used, often adding up to something like a day, but not strictly. It is obvious that operational, logistic restrictions may make measurement of full 24 hours sessions difficult or impossible in field conditions; for permanent GPS stations, this is routine.

3 The monitoring networks

3.1
Network geometry

The networks established had diameters of several kilometers. As the depth of the envisaged repository would be on the order of 500 m, this is the right area size to detect crustal deformations of relevance to the tectonic stability of the crustal rock in which it is embedded.

It is known that in the areas considered the crust contains fracture zones, which are actually depicted in the Olkiluoto site map included in the reports. The local networks, which count 7-10 points, can be seen (Olkiluoto) or assumed (Kivetty, Romuvaara) to straddle many such faults. In Olkiluoto, the nuclear power plant lies within the network, at its edge.

The national permanent GPS network FinnRef covers an area criss-crossed by thousands of fault lines, and the possibility for detecting motions happening along any of these is correspondingly greater. On the other hand, GPS observations tend to produce less precise, less accurate and more uncertain vectors over these larger distances, which are more easily contaminated by fractious systematics due to a broad spectrum of effects related to the measurement technique, the satellite orbits, the atmosphere, the environment, and what not.

The choice of establishing three local networks for episodic monitoring, as well as a permanent network of which three stations are located one within each of these networks, is a fortunate one.

3.2
Pillars

3.2.1 Construction

The pillars were constructed in the following way (Chen and Kakkuri (1995)). Two metre tall concrete pillars with a diameter of 35 cm and a steel plate on top, in which a 5/8 in. hole was drilled accommodating the bolt that attaches either a GPS antenna or an industry standard theodolite.

An important element in constructing the pillars was the solar radiation protection shield, a cylindrical metal sheet around the pillar but not touching it, keeping out direct sunlight.

In the course of the day and the year, the pillars will undergo thermal expansion and contraction with variations in ambient temperature. The thermal expansion coeffcient of concrete may vary between 8 and 12 µm/m/°C (http://www.tfhrc.gov/pavement/pccp/thermal.htm), which for an annual temperature range of 60°C would produce a height variation range of the pillars of 1.2 mm, large enough to require taking into account. As all three sites are small, one may assume ambient temperature around all the pillars within each site to be the same. What one may however not assume, is that the impact of solar radiation is identical for all pillars, due to variation of the surrounding forest. This is where the solar radiation shield comes in.

Another problem with directly impacting solar radiation is, that it heats the pillar unevenly and thus produces bending and even torsion of the pillar. This can be a particularly intractable problem, but is no worry here.

The maximum centering error produced by the steel plate attachment was investigated and found to be below 0.3 mm.

3.2.2 Stability monitoring

In 2000, for the first time the positions of the local pillars relative to specially created reserve markers were measured precisely using a theodolite, a precise electronic distance meter, and GPS (Ollikainen and Kakkuri (2001)). These measurements are essential in order to guard against the possibility, that motions actually found between pillars might be due to pillar movement or deformation relative to the local rock base, rather than bedrock deformation.

The ground reference points (reserve markers) were already created in Olkiluoto in 1994 (Chen and Kakkuri (1995) p. 3) and in Kivetty and Romuvaara in 1995 (Chen and Kakkuri (1996) pp. 13, 19).

Although the risk posed by not having these local reserve markers is small, one hates to think of the possibility of small but significant-looking local movements having been detected before they were in place and their initial connection measurements with the pillars were done. Anyway, it is good to have them now.

3.3
Landscape and sky visibility

The three areas studied are all covered with forest of varying height. In the working reports, mention is made of the sky view of the points, stating (Chen and Kakkuri (1995). p. 6, for Olkiluoto only) that “the sky view is open enough for every station”. More detail could not be found. The Bernese processing listings state a cut-off angle of 20°, suggestive of a free horizon comparable to this. Also site photographs tend to show fairly open horizons. Factual information would be welcome, however.

Important for the value of prolonged measurement time series is also the constancy of the horizon. Trees that grow, are felled, and grow again may produce intractable systematic effects if allowed to affect the measurement horizon.

Another problem at Olkiluoto was the magnetic effect of power wires overhead, which disturbed the antenna compasses used for orienting them correctly. Therefore a local mark was made for each pillar to give the correct North direction for all subsequent measurements. A wise arrangement. In GPS measurements the antenna should be oriented *approximately* North; more important than the correctness of this orientation, which cancels out to first order in difference measurements, is its *consistency* between measurements made at different times.

4 Measurement strategies

4.1
Observation sessions and duration

In the earliest measurements (1995–1996), measurement session durations of 6–10 hours were typically used, and receivers moved from point to point between sessions. As no more than four to six receiver/antenna pairs were available for ten points including the permanent reference station, this was an operational necessity.

From 1997 onward, the situation improved somewhat, as on most stations two or three sessions were observed to a total duration of almost 24 hours, sometimes even more. Still, at the Olkiluoto site there would be typically two points where only one session was measured. On the other two sites, near-24-hour observations on all points were usually made.

Clearly these limitations are imposed by the logistics of measurement and availability of equipment. Still, the importance of measuring full 24 hours measurements should be underlined, even if that causes added expences.

4.2
Measurement repeat strategy

The measurements were typically repeated half-yearly, as the below summary describes:

Year	First measurement	Second measurement
1994	Tests only (Olkiluoto)	
1995	May 25–28 (Olkiluoto only)	Oct 3–5 (Olkiluoto only)
1996	April 24–25, May 7–8, 9–10, July 12	Oct 1–2, 23–24, 29–31
1997	May 6–7, 13–15	Oct 2–5
1998	May 7–14	Oct 2–7
1999	May 3–7	Oct 1–6
2000	No measurement due to solar activity	

The fair consistency evident from this little table is very important for deriving secular effects in a consistent way which is insensitive to all kinds of seasonal variations, which we know to affect GPS measurements, e.g., through the atmosphere. This looks like careful planning.

Meteorological measurements were done in 1995, but it was soon found that better results are actually obtained by processing using a standard atmosphere model. Therefore these measurements were discontinued.

5 Processing strategies

5.1

The Bernese software and its use

The Bernese GPS software (Beutler et al. (2001)) was used in processing the observations. Version 3.5 originally, version 4.0 from 1998 onward, cf. Ollikainen and Kakkuri (1999) p. 2.

For ordinary applications, GPS observations are usually processed using software provided by the receiver vendors; occasionally software is used from specialized software suppliers, usually optimized for convenience and ease of use.

One problem with this kind of software is, that while they are easy to use and make lightly trained personnel quickly productive, they are “black boxes”. For scientific applications this is a serious drawback. A hallmark of scientificness is tractability of procedures and results, and black boxes fit in poorly with that principle.

Bernese is one of a number of GPS software packages (Gypsy; Gamit; …) that come with source code. The user is even required to build from source for the installation he will be using it on, making mandatory a measure of intimate knowledge with the technology and a certain preparedness to tinker. Bernese, like Unix, is user-friendly; but—it picks its friends with great discretion. The user interface consists of a series of text screens operated strictly through the keyboard. The manual boasts 500 pages, but doesn't even document all the ins and outs. It is considered good enough to be used for routine data processing of continent-wide networks of permanent GPS stations, so should suffice for the task at hand as well.

5.2

Physical models used

The Bernese software is a complex system; it models a great many physical effects that are relevant not only to the measurement process, but also to the behaviour of GPS satellites as celestial bodies and that of the Earth as a planet.

1. Orbital motion of the GPS satellites, including non-inertial forces such as radiation pressure;
2. Effects of other celestial bodies, like Sun, Moon and greater planets;
3. The effect of the attitude of the GPS satellites on the measurement;
4. The behaviour of GPS clocks;
5. Earth rotation parameters like polar motion and length of day;
6. Earth tides, ocean tides and the elastic response of the solid Earth to these;
7. The effects of antenna type on error propagation;
8. The propagation effects of ionosphere and neutral atmosphere;
9. Finally, what is not strictly a physical phenomenon is the choice of reference frame to compute in and co-ordinate frame transformations.

5.3

Temporal trend studies

These studies were done both using the local deformation network measurements and the nation-wide FinnRef data collected over the years.

It will be clear that, while in the local areas the only significant deformations to be expected are crustal fault motions, nation-wide one should expect also larger scale continuous deformations, such as those related to the post-glacial land uplift. Periodic Earth tidal deformations will of course also occur, but will not be visible in long term trend studies.

5.3.1 Local studies

A number of studies are reported through the years. For 1996 no deformation analysis was done due to the still too short time span, but already for 1997 an attempt was made, leading however to the justified conclusion:

> *"As the movements are so small, six measurements are not enough to make a firm conclusion. But the picture of the local movements is becoming visible, a more reliable conclusion can be made after two more years observations."*

However, as an example, the number of "outliers" among the 45 inter-point vectors—or equivalently, the estimated rate of change—at the Olkiluoto site behaves as follows:

Year		**Number**	
	(45)	(21)	(21)
1996		Too early	
1997	11	3	4
1998	4	0	6
1999	9	2	3
2000		Solar activity	

These numbers are based on a normal distribution two-sided significance level of 95%.

Clearly even at the time of writing, no more reliable conclusions can be drawn yet. This is no criticism of the work, but rather testimony to the exceeding difficulty of detecting such minute motions. The work must go on.

5.3.2 Nation-wide studies

The reports contain several studies using stations belonging to the FinnRef network, on secular changes in co-ordinate differences and baseline lengths between station pairs.

There is known to be a large scale continuous crustal deformation going on in Fennoscandia due to the post-glacial rebound, which started with the retreat of the continental ice sheet at the end of the last ice age 11000 years ago. This motion is in reality three-dimensional, though the traditionally studied—and best known—part of it is its vertical part, the uplift. GPS allows the study of this phenomenon as the spatial deformation it is (Milne et al. (2001)).

In the reports the following baseline components and lengths are studied concerning their secular trends or "velocities":

Year	**From**	**To**	**Component**	**Reference**
1994	M'hovi, Tromsø, Onsala, Wettzell	Olkiluoto	Initial co-ordinates	Chen and Kakkuri (1995) pp. 1–3
1995	M'hovi, Tromsø, Onsala, Wettzell	Kivetty, Romuvaara	Initial co-ordinates	Chen and Kakkuri (1996) pp. 14–16, 19–21
1996	Metsähovi	Olkiluoto, Tuorla, Kivetty, Romuvaara	Length, N, E, h	Chen and Kakkuri (1997) pp. 5–17, 25–29, 39
1997	Metsähovi	Olkiluoto, Tuorla, Kivetty	Length, N, E, h	Chen and Kakkuri (1998) pp. 6–12,
1998	Metsähovi	Olkiluoto, Tuorla, Kivetty, Romuvaara	Length, N, E, h	Ollikainen and Kakkuri (1999) pp. 10–14, 22–24, 29–31
1999	Metsähovi	Olkiluoto, Tuorla, Kivetty, Romuvaara	Length, N, E, h	Ollikainen and Kakkuri (2000) pp. 7–11, 19–21, 27–29
2000	Metsähovi	Olkiluoto, Tuorla, Kivetty, Romuvaara	Length, N, E, h	Ollikainen and Kakkuri (2001) pp. 3–7, 11–13, 16–18

In the later publications even formal velocity estimates with their error estimates are presented. In Ollikainen and Kakkuri (2001), values are presented (Table 1 on page 7 for Olkiluoto and Tuorla only; strangely enough no corresponding table for Kivetty and Romuvaara, but a summary Table 6 on page 27—but there again without error estimates!) which are highly significant for the heights, but still barely significant only for the other components and the baseline lengths. The caveat must be made here about the applicability of simple linear regression on data points that are undoubtedly correlated. See Section 6.5 for more on this.

Also a comparison of GPS-derived and precise levelling derived uplift rated (both of them expressed relative to Metsähovi) was found to give good agreement (page 28), as did a comparison of horizontal velocity components with the NUVEL1A global plate motion model.

What this tells us is, that GPS is a fine technique for studying and monitoring these two so different, large scale geodynamical phenomena. The level of agreement found, typically up to half a mm/year, tells us something about the sensitivity level of the GPS technique for detecting motions over a time scale of some five years.

6 Precision, reliability and trustworthiness

6.1
Quality of the GPS observations

From numerous plots and tables included in the reports one gets a clear impression of the quality of the GPS observations obtained; there is no doubt that the equipment used produces data of the required precision at least most of the time. And when not, appropriate testing of observation quality in the context of processing will remove questionable observational material.

6.2
Unmodelled physical effects and their significance

In the nation-wide studies, the number of relevant physical effects to be modelled will be much greater due to the greater vector lengths. Many of these effects are already taken into account, such as

1. The solid Earth tides (decimetre level) are corrected within the Bernese software using a standard model
2. Ionospheric effects are eliminated by using the ionosphere free linear combination observable in the final solution
3. Tropospheric effects are eliminated by
    (a) applying a standard model and
    (b) estimation of the residual effect (per station and per time period) relative to this
4. Antenna specific delay patterns are corrected for within the Bernese software using tables based on laboratory measurements
5. Local multipath effects (ground reflections) are not corrected for
6. Local effects of snow and ice accumulation, which can be significant, are not corrected for except by omission of seriously affected observations.

From the descriptions given, all these effects are taken into account as well as is possible; residual effects will tend to average over the long span. The geophysical main objective of the nationwide FinnRef network deformation studies is to study all crustal deformations occurring on the Finnish territory, among which especially the post-glacial rebound in both the vertical and the horizontal components.

6.3
Critique of tropospheric modelling

Customarily in a small area one estimates tropospheric delay parameters *relatively*, i.e., one keeps those of one reference station fixed to a standard atmosphere model, and solve for the others relative to this. However, doing so may introduce a scale error into the local network by misrepresenting the bulk effect of the neutral atmosphere. The scale effect will tend to display a periodicity caused by the seasonal periodicity of the thickness of the wet and dry atmosphere, with a dominant period of one year. This in addition to non-periodic effects.

Another tropospheric refraction modelling limitation to consider is the inaccuracy of the "cosine model" for neutral-atmosphere ("tropospheric") delay as a function of zenith angle. In the newest version of the Bernese software, the improved Neill mapping function ought to take care of this.

It is encouraging to see secular patterns suggestive of post-glacial rebound appear in the coordinate differences, e.g, Ollikainen and Kakkuri (2001) pp. 4–7, 12–13, 17–18. However, in these same graphs, also annual periodic patterns can be seen, which are grounds for caution. Any extreme events of a tectonic nature would have to be at the several-millimetre level to be detectable by the FinnRef infrastructure, and as of now, there do not appear to have happened such events.

As to the annual periodic patterns seen, especially in the baseline lengths between Metsähovi and the permanent stations considered, various explanations are possible. As noted, the cause could be the use of a standard reference atmosphere (Saastamoinen model, 18°C, 1013.25 mBar, 50% relative humidity at zero height level) which will differ seasonally from the true atmosphere. Even if absolute tropospheric zenith delays are estimated—as is technically possible for a network spanning the latitude range of Finland—still it is likely that the standard atmosphere assumption is present in the final solution with a non-zero weight, causing biases.

Recent results (e.g, http://www.fgi.fi/osastot/geodesia/projektit/finnref/#5) seem to indicate that the problem of seasonal systematics has mostly disappeared using the latest software based on the Neill mapping function. Then again, in Ollikainen and Kakkuri (2001) pp. 25–26 a discussion is presented on the periodical baseline length change, where the amplitude and phase of the yearly periodicity are derived using data over a period of 4.5 years, and the effect is found to be quite pronounced, and as yet without satisfactory explanation. On the other hand, being a periodic effect, it should not seriously interfere with the objective of the work.

It might be interesting to study the effect on processing results of choosing, instead of a standard atmosphere, one based on more actual conditions. One may suggest true air pressure and seasonal mean (if not true) temperature, which together with a standard relative humidity of 50% ought to produce more realistic water vapour integrals.

6.4
Critique of ionospheric modelling

In the local studies, one important unmodelled—or rather, imperfectly modelled—physical effect that one is led to believe to have an influence on the results is the inherent limitation of the single layer polynomial expansion model for ionospheric total electron content.

If this modelling is done incorrectly, the result may be spurious azimuth-dependent changes in the lengths of baselines. Examples of this are graphically illustrated.

According to practical experience, the technique used of modelling the ionospheric total electron content as a relatively simple polynomial of latitude and solar hour angle relative to their reference values, works only properly under conditions of fairly quiet ionosphere.

Theoretically, the method suffers from the problem that all empirical polynomial modellings of physical phenomena suffer from, that of *representational instability* for higher degrees of the polynomial. Especially under restless ionospheric conditions, one may expect not only the ionospheric noise to propagate unfavourably back into the adjustment results, but more seriously, to produce erroneous ionospheric model parameter estimates.

An even worse potential trouble spot however is the choice of a *single layer representation* of the total electron content, while the true electron distribution is three-dimensional. This is especially dangerous when estimating the horizontal distribution of electron density from observations made at only a single station. An erroneous assumption on the height of this layer will produce a perfect-looking model, that however contains a scale error originating directly from the relative wrongness of the height of the layer. This could explain part or all of the scaling errors observed and should be looked into.

The technique of using an epoch-by-epoch ionosphere free linear combination as input data does not suffer from these problems, but, as said, the price paid is a three times higher noise level.

In the reports some attention is given to this problem complex (Ollikainen and Kakkuri (1999) pp. 3–8; Ollikainen and Kakkuri (2000) pp. 3–5); however, one would have appreciated a more formal analysis, using

1. the residuals produced by the estimation of the ionospheric model parameter set;
2. a comparison between co-ordinate results obtained using ionospheric polynomial model estimation, and the conventional technique of using ionosphere-free linear combination observations;
3. using data from more than one station, and study the effect of varying the representative height of the single layer ionosphere model on the residuals of ionospheric model parameters fit obtained. In the descriptions, the height of the single layer isn't even mentioned as a parameter! One has to read the attached Bernese computation listings to discover that a fixed value of 400 km is used.

One would also like to discuss with the Bernese software group possibilities for better model parametrization for these local studies. As an essential minimum, the representative height of the single layer ionosphere model should be made an estimable parameter.

Such co-operation would hardly fall within the commissioning framework; I want to suggest it for the future.

6.5
Confidence limits and reliability

In the literature, extensive references can be found to proper statistical testing methodologies. See, e.g., Baarda (1968) for a description on how to design a testing strategy for network adjustment, aimed at:

1. Finding out whether the models used are valid and “good enough” for the adjustment problem at hand;
2. If any, and if so, which, observation(s) contain(s) gross errors;
3. How good are the prospects for identifying errors of a certain magnitude (internal reliability); and
4. What will be the effect of remaining (undetected) gross errors on the network solution (external reliability).

In the reports reviewed, such an advanced method was not used, which is common practice and acceptable if a measure of common sense is used instead in judging the results of the network computation. The reason why I am saying this, is that the prerequisites for applying, e.g., the Baarda theory, are rarely if ever fulfilled in practice.

1. Distributions of random observation error are rarely if ever normally distributed, i.e., conforming to the Gaussian error curve. There is no sharp distinction between random errors and more rarely occurring small gross errors, which tend to inflate the tails of the distribution relative to the Gaussian one.
2. Random errors in different observations—e.g., observations obtained at successive epochs—are generally correlated at a level depending on their temporal separation; a phenomenon very hard to model correctly, and which, e.g., the Bernese software doesn't even try to do.

The consequence of the latter circumstance is simply, that one can never trust formal error estimates produced by software working in this way. *A priori standard errors are invariably too optimistic!* As experience has shown, easily by an order of magnitude.

Therefore in practical work, *a posteriori* error estimates must be, and are, used. Typically one uses estimates of quantities that “ought to” be zero (like closing errors or differences between two estimates of the same quantity). These are then compared with an empirically determined, *a posteriori* standard deviation for them, rejecting the result if it exceeds (e.g.) three times this standard deviation (“three-sigma criterion”).

The first circumstance above however, the non-normality of typical observational random error distributions, warrants the use of even wider rejection bounds, even as much as five times the standard deviation.

Note that the above applies just as well to results of the often used, simple linear regression!

7 Relevance of studies for establishing site stability

7.1
Role of geodesy and other disciplines

It will be clear that geodetic measurements as performed on the three sites and over Finland as a whole can only be a part of a programme to assess the role of site stability in safeguarding containment of the repository to be constructed. What it can produce, is knowledge that crustal movements of a certain magnitude have actually occurred in one or more of the areas of study; or knowledge that such motions exceeding a given treshold have not occurred in the areas of study during the time span during which measurements have been made. And as such, it is only one technique able to give such information, seismology being another.

Also, the relevance of such findings for conditions wholly different from those existing today, such as during glaciation cycles, should be left to the judgement of geological experts.

7.2
Limitations of spatial and temporal sampling

Obviously the three areas where local crustal deformation studies have been made are very small in extent, and the time span of measurement has been limited to only less than a decade. What this means is, that a negative result—no motions found—does not mean that such motions do not take place. In fact, geologists believe that even old crust like the Fennoscandian Shield consists of micro-plates that are in continual small movements along a network of fault lines permeating the crust. Yet, the frequency of movements of a sufficient magnitude to be detected by GPS in these small test areas may be too low to have actually occurred with any plausibility in the time span of only half a decade.

7.3
About frequency distributions of extreme events

What one has to do, in order to gain an understanding on the relevance of the geodetic measurements, is to consider independent information on these crustal motions, such as, e.g., earthquake studies can provide. Earthquakes are associated with sudden motion along fault lines; however, not all such motion produces earthquakes, there may be aseismic motions. Conversely, not all motions that can be seismically observed will necessarily produce geodetically observable displacements at the surface.

It is well known, see, e.g., http://www.hpl.hp.com/shl/papers/ranking/ranking.html, that a great many phenomena including earthquakes display a power law relationship between limiting magnitude and frequency of occurrence. On a log-log plot this displays as a straight line. Such a power law can be used to infer *a priori* probabilities of crustal motion events of a certain magnitude or over occurring. Geodetic observations of actual crustal surface displacements can then be connected with this—if they can be observed at all. More generally, the study of extreme events and their frequency distributions is highly relevant for the issue at hand. See, e.g., Sornette et al. (1996), Caers et al. (1998), and many more to get a taste of this rapidly developing field. This is the value of geodetic measurements in a multidisciplinary context.

The importance of observing with confidence at least some crustal motion events in the Finnish crust by geodetic means should be stressed. It allows us to connect, in the way of scaling or calibration, the abundant observations of seismic activity with the geometrical displacements provided by geodetic means. If the three local test areas do not produce such events, one should look at the measurements of FinnRef covering the whole country. While the vectors of this network obviously cannot be determined to the same absolute accuracy, they cover a much greater area, and the continuity of observations partly makes up for the effect of longer vectors.

A review of international work on connecting seismic events with geodetically measured displacements would also be indicated, as some material of this kind exists. Most of it appears to concentrate on seismically active zones (however, see http://www.ngu.no/neonor/) and one should expect this not to be directly transposable to the Fennoscandian shield area.

8 Conclusions and recommendations

8.1
Evaluation of the GPS deformation studies

On the whole, the GPS deformation studies in the sites Olkiluoto, Kivetty and Romuvaara, as well as the studies over the whole territory of Finland using the FinnRef permanent network of 12 permanent stations including those on the abovementioned three sites, have been performed professionally using state of the art equipment, measurement and analysis techniques by competent personnel well versed in the art and science of highly precise deformation measurements by GPS.

As always in large operations of this kind, occasionally things do not go as planned. One has to be prepared for this and be able to improvise or settle for next best, and the reports show that the crews responsible for these works were well capable of handling this.

More detailed technical evaluations of many planning decisions can be found in the text above.

There are a few things that could be improved, as discussed below. This does not mean that the results obtained using the methods and techniques described in the series of technical reports would not be state of the art, or would not provide valuable material for drawing conclusions, on the contrary. The available material is the best of its kind that could have been collected, and quite probably unique even in a global context.

8.2
Suggestions and recommendations

As effects were found due to both tropospheric (section 6.3) and ionospheric (6.4) modelling which influence the scale of the local control networks, it appears prudent to obtain independent information on the behaviour of the scale of the network by monitoring selected baselines using the alternative technology of electro-optical distance measurement. It is advisable to have vectors in both directions, west-east and north-south, as an azimuth dependence was seen in the beforementioned scale effect.

The reserve markers created at the pillars in the three test areas should be regularly used for their intended purpose, establishing the stability of the pillars themselves relative to their bedrock foundation. Tacheometric monitoring measurements every third year, as is customary for the Finnish tide gauges, could be considered and would not be excessive.

The GPS measurements should be done in a way that on each point, a full 24 hour GPS cycle is measured, even if in several sessions. It is now understood that this effectively eliminates some systematic effects with a 24 hour cycle, as well as those related to the GPS satellites' 12 hour orbital period. Most clearly this has been seen in the literature when processing extended permanent GPS monitoring networks, but one must expect this to be the case also locally, if the highest precision is aimed for.

I suggest experimentation, especially in the FinnRef processing, with use, together with zenith delay estimation, of more realistic neutral atmospheric representations than the standard Saastamoinen model, in order to eliminate the last vestiges of what appear to be seasonal periodic systematics. In the local processing, a new hard look at the ionosphere model parametrization would seem indicated.

Currently the measurements, and especially those made with state of the art receivers and antennas, span barely half a decade. Because of the profound effect that solar and magnetospheric activity ("space weather") has on geodetic GPS measurement on our latitudes, I would recommend to continue the regular measurement programme until at least one full[1] solar activity cycle, 11 years, has been completed.

Finally I stress, no doubt superfluously, the importance of close interdisciplinary collaboration between geodesists and representatives of other disciplines.

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[1] In fact, this is half a cycle, as the solar magnetic field is reversed every 11 years.

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