# Draft plan for absolute gravity campaigns in the Fennoscandian land uplift area

Compiled by Jaakko Mäkinen, with support especially from Hans-Georg Scherneck, Björn Engen, Andreas Engfeldt, Gabriel Strykowski, Ludger Timmen, Herbert Wilmes.

## 1. Purpose of plan

The plan strives to present a basis for coordinating absolute gravity measurements that serve the study of the postglacial rebound (PGR) in the Fennoscandian area. It is not concerned with, say, the absolute measurement of calibration lines for relative meters, or with the determination of gravity values as an accessory for metrology. Geographically, we limit ourselves to the Nordic and Baltic countries. Greenland and Iceland thus fall outside the planning area. This could be questioned but on the other hand the collapse of the forebulge is still affecting gravity as far as Netherlands, and we might end up including most of Europe. One can also argue that Ny Alesund in Svalbard depends on the Barents Sea deglaciation and not on the Fennoscandian one. Ny Alesund is in fact excluded from this document, not on the grounds above, but because it appears that measurements might be best coordinated bilaterally with the Norwegian Mapping Agency, using the FP6 follow-up "Transnational Access" (if successful) to the "Access to Research Infrastructures Activity" in the now-ended IHP (see (http://npolar.no/nyaa-lsf/). Suffice to say here that annual absolute-gravity measurements at Ny Alesund are highly desirable.

## 2. Instrumental and financial premises for measurements

Based on information available in March 2003:
(a) IfE Hannover has finance and personnel/instrument (FG5) capacity to observe 10-12 stations annually in the area, starting in 2003.
(b) FGI has finance and personnel/instrument (FG5) to observe 10-12 stations annually in Finland, plus 2-3 in Sweden and Norway, the latter primarily for instrument comparison, starting in 2003. Long-standing bilateral agreements call for altogether 6-7 stations in Estonia and Latvia in 2003.
(c) BKG will measure eight stations with FG5 in Sweden and Norway in 2003, plus a comparison measurement in Finland. After that there will be a pause in their engagement.
(d) A funding application for a joint Nordic absolute gravimeter will be placed by institutions in Norway and Sweden in 2003. If the application is successful, the instrument could be available for the field campaign in 2004.

## 3. Station choice

**NGGOS/AG stations**. The report by Scherneck et al. (2002) presents a fundamental set of stations, the point of departure for any plan. The stations proposed by the countries were *Metsähovi, Vaasa, Joensuu, Sodankylä* (Finland); *Onsala, Mårtsbo, Skellefteå, Kiruna, Kramfors, Östersund/Norderåsen* (Sweden); *Tebstrup, Elsinore/Helsingör, Copenhagen* (Denmark). Norway refrained from making a proposal but the report deduces that at least *Trysil* and *Tromsö* continue to have high priority.

**Expanding the set of stations**. The NGGOS/AG set was chosen at a time of paucity of resources: the report discusses a 5-year (or less) repeat rate at the 15-odd stations. The recent increase in resources now allows annual repeats at 20 stations of more. In which proportion should the increase in sampling density be used on time and on space? In other words, should we have few stations and measure on them very often, or a lot of stations and measure on them more infrequently? This will be discussed in the Appendix; for the moment we assume that typically stations are measured once a year.

## 4. Inventory of candidate sites: NGGOS/AG, old absolute, permanent GPS, tide gauges

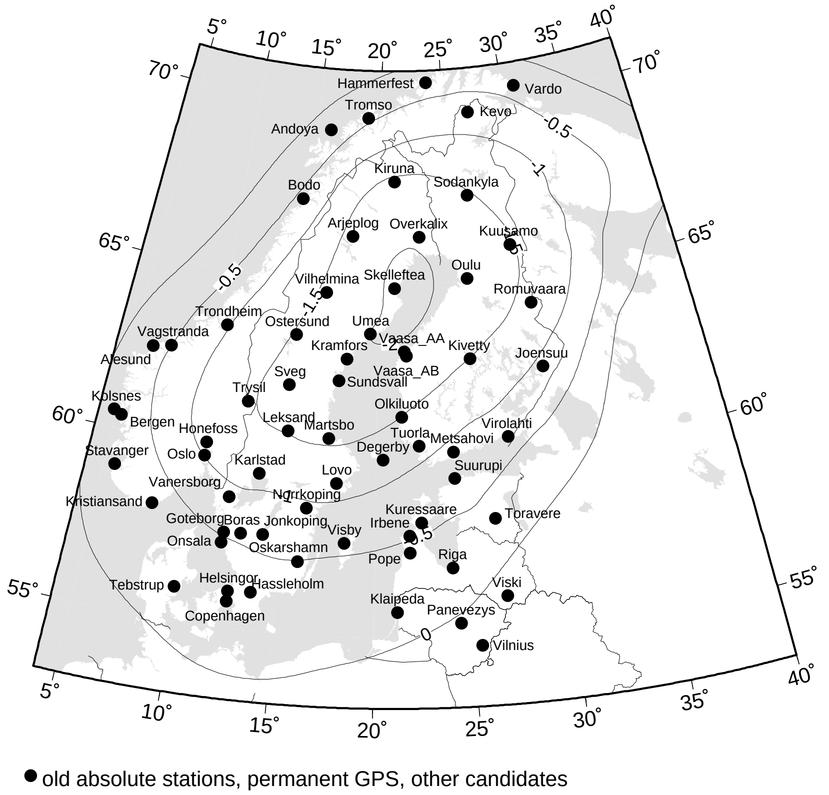


**Figure 1**. The maximum set from which it is proposed that the absolute stations be chosen (see text). The curves show expected gravity change in µgal/yr. They were obtained from the land uplift isobases of Ekman (1996) with the following procedure: (i) a geographic grid which reproduces the isobase values was generated using the spline method of Wessel and Smith (1990); the same splines were used to extrapolate values down to –1.5 mm/yr (2) uplift relative to MSL was transformed to uplift relative to the geoid by adding an estimated eustatic rate in MSL 1.2 mm/yr, (3) uplift relative to the geoid was multiplied by -0.216 µgal/mm to get the gravity rate (Ekman and Mäkinen, 1996), (4) curves were generated from the grid thus obtained. I apologize for the "simplified" orthography of the station names.

Figure 1 shows the maximum set of candidate sites from which we propose to select the absolute stations. It includes (a) the NGGOS/AG stations, (b) old absolute-gravity stations, (c) permanent GPS stations, (d) the end and center points of the land uplift gravity line 63ºN, with time series 1966–2002. Note that all stations (a) are included in one of the other categories. Next, we present the old absolute stations (Figure 2) and permanent GPS stations (Figure 3) in more detail.

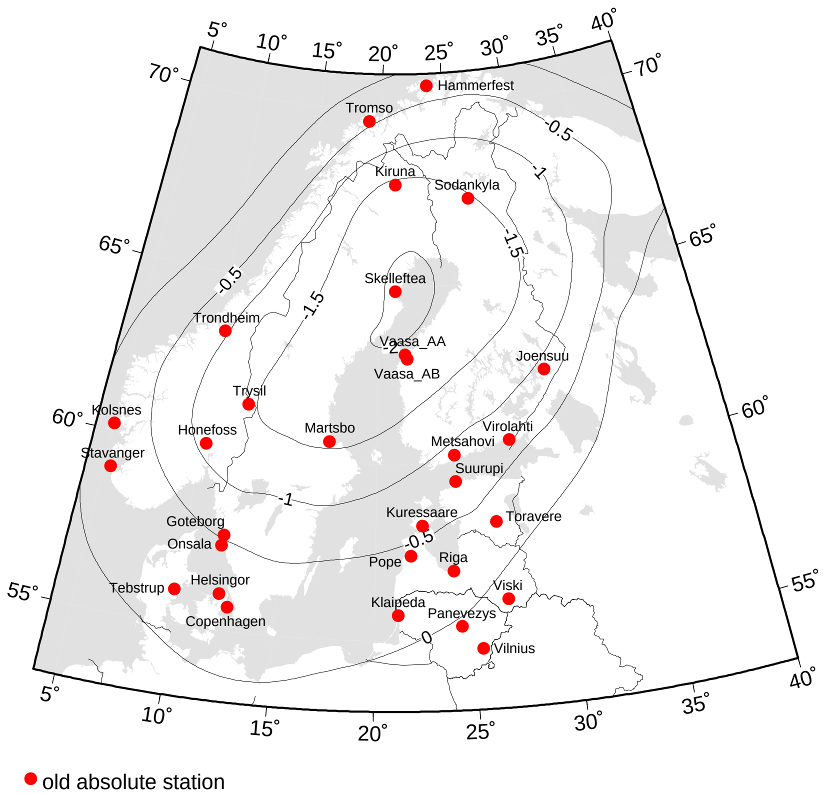


**Figure 2**. Known absolute gravity stations in the Fennoscandian land uplift area. Omissions: (1) The Troll oil drilling platform, (2) Ilmala, Masala and Vihti (all around Metsähovi) are represented by Metsähovi alone. (d) Ilomantsi east of Joensuu, (e) the unpublished measurement by Arnautov (ANSSSR) using GABL at Tallinn Technical University.

Of the stations shown, Hammerfest has been abandoned (reportedly changed by building works), details on Kolsnes are not known, Copenhagen at the old KMS headquarters in Gamlehave Alle will be abandoned and replaced by a new station this year, and Helsingör in a school corridor is apparently not deemed suitable for geodynamic work. Further work at Göteborg (in the main building of Chalmers Technical University) quite close to the Onsala site is probably not profitable.

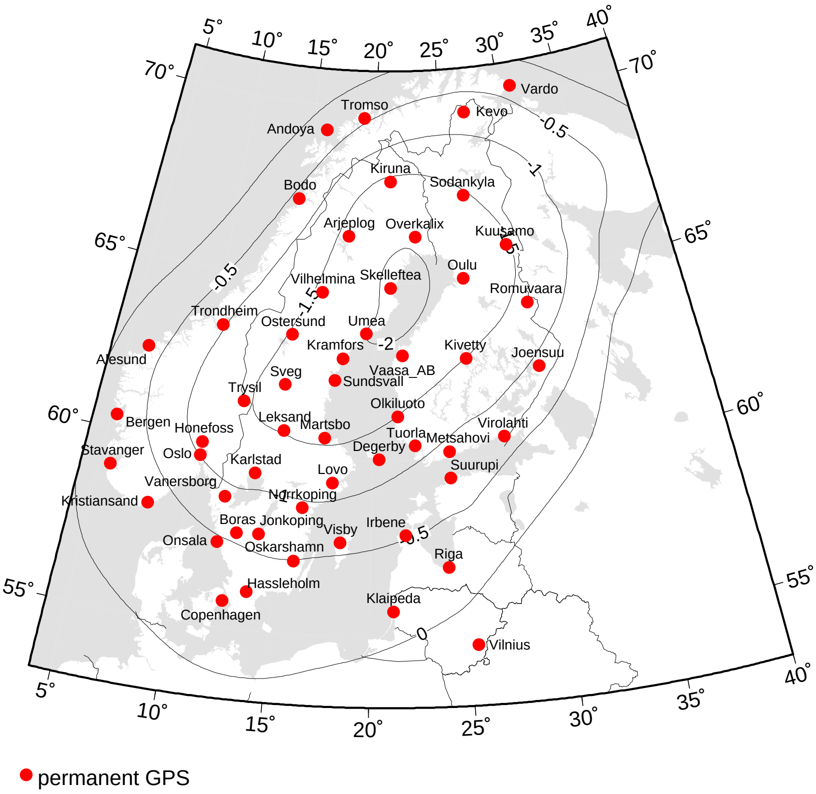


**Figure 3**. Permanent GPS stations by the end of 2003. In Norway, the list is known to be incomplete. In Sweden, Uppsala is not shown. In Denmark, the station Copenhagen (Buddinge) apparently coincides neither with the old nor with the new absolute station. Two more permanent stations Denmark (Aalborg and Vejle) are not shown. Kramfors and Klaipéda will be set up during 2003.

Another relevant issue for the location of absolute stations is the proximity to tide gauges (Figure 4). Since the influential reports by Carter et al. (1989, 1994), the use of repeated absolute gravity to monitor TG stability or to separate vertical land motion from sea level change has become widespread, and such work is obviously important to the study of PGR.

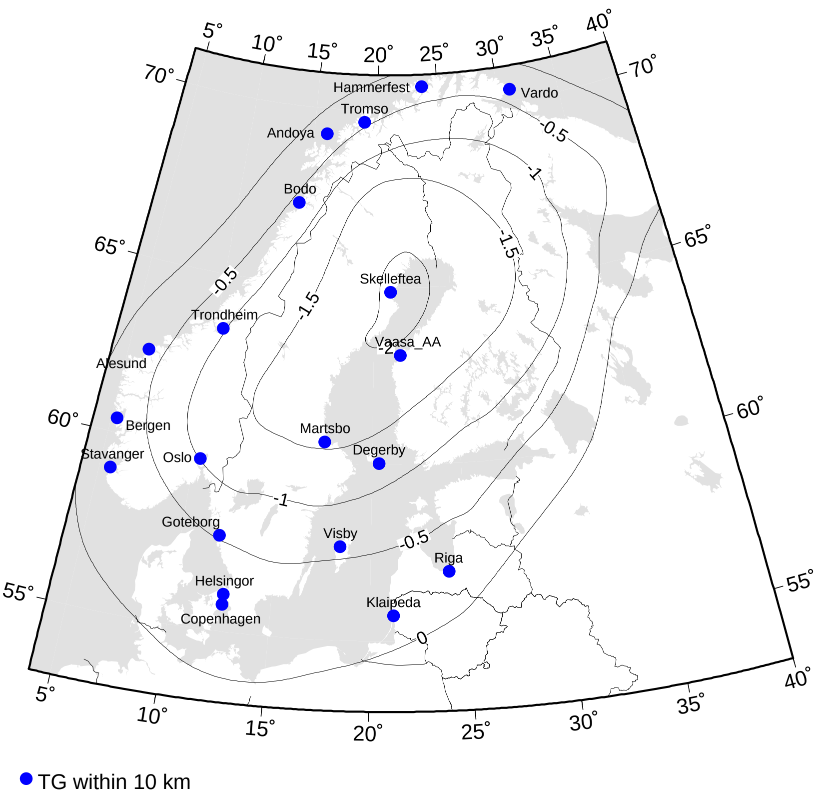


**Figure 4**. Sites of Figure 1 that are (nominally) at most 10 km from a tide gauge. The list is probably incomplete. Often it is assumed that due to possible local or regional instability, the absolute gravity site (or the permanent GPS station) must be quite close to the TG. Then 10 km is frequently applied as a criterion of proximity in data collection. This is perhaps not a relevant figure in large parts of Fennoscandia, where the TG and its reference bench mark can be placed on crystalline bedrock and monitored using repeated levelling. Applying 20 km would enlarge the list greatly.

Remarks: Riga TG is known to suffer from river effects. Andöya and Klaipéda are ESEAS-RI sites, and Andöya has the tandem GPS setup.

A subject that must be addressed here is the proposal for the European Combined Geodetic Network ECGN. The first call for participation has recently been issued, with the deadline May 15, 2003. The call is for implementation of the stations. Roughly speaking, the purpose of the network is to combine “geometric” and “gravity” techniques in the monitoring of the European Reference Frame for both “spatial” and “gravity-related” positions, the latter meaning heights. The realization goes somewhat like this:

- take the subset of EUREF permanent GPS network (EPN) stations that have levelling connections
- add European superconducting gravimeter (SG) sites and provide them with GPS if not yet in EPN
- add some tide gauge stations to the EPN
- repeat absolute gravity on all types of sites; repeat rate on non-SG sites is perhaps 1/year or more realistically 1/(2 years)

Thus repeated absolute gravity is a prerequisite for inclusion in the ECGN, which makes the station choice important for us. Of course, a permanent GPS station with repeated absolute gravity does not become any better for geodynamics from being a part of ECGN. The point is that getting the absolute gravimeter to the station in the first place might be in some way facilitated by the ECGN banner. So far, hardly any ECGN discussion appears to have taken place in the Nordic countries.

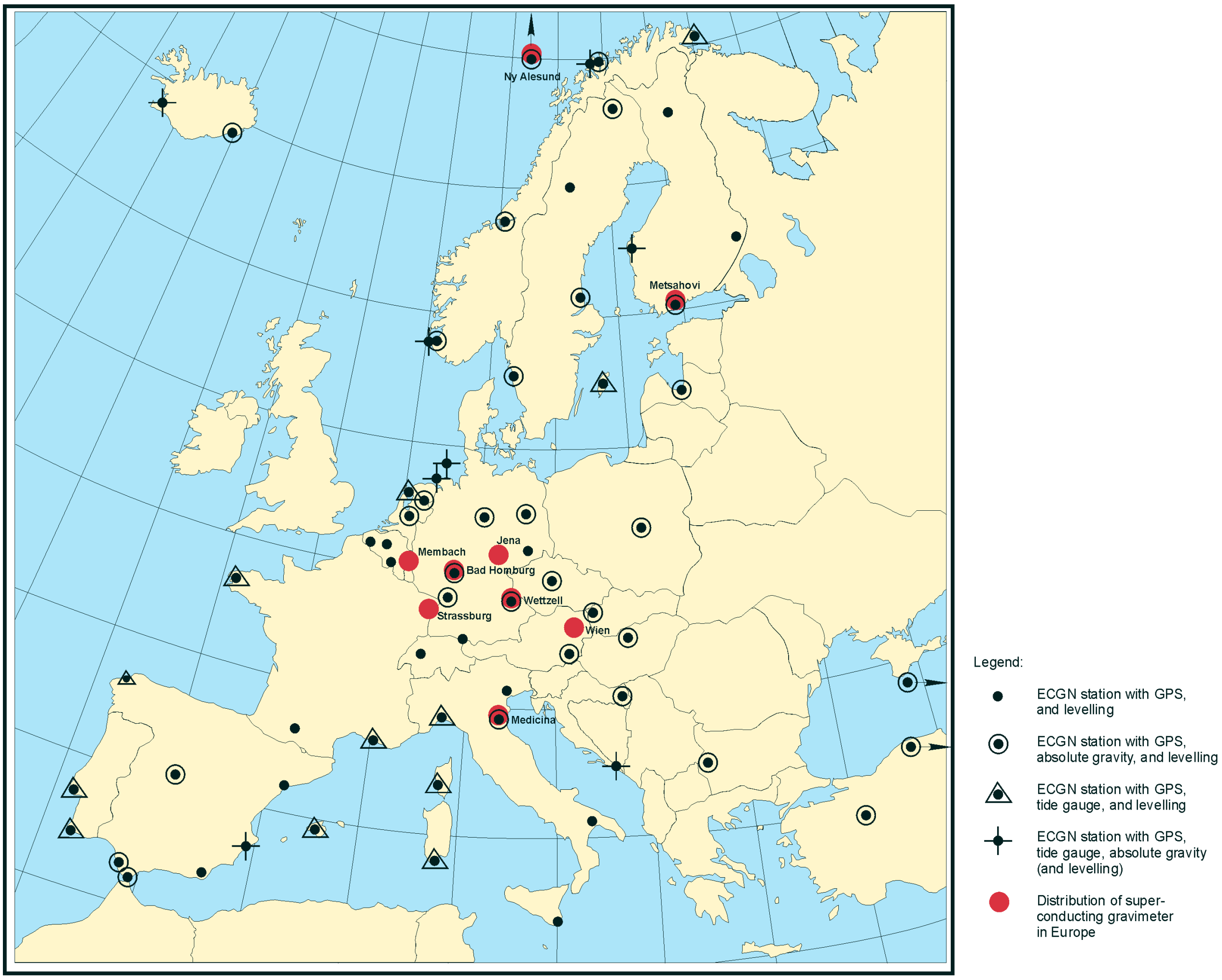


**Figure 5**. Draft plan of the European Combined Geodetic Network (ECGN). (Vaasa, Joensuu and Sodankylä do have absolute gravity, the map is in error.) The sites are only candidates and in order to be included need to be proposed by the responsible institutions. Other stations may be suggested too. However, to limit an expansion of the EPN they should preferably be existing EPN stations and in our study area the map is nearly exhaustive on EPN: only Copenhagen, Borås and Vilnius are not shown. Vilhelmina, the Swedish station with a simple dot is in a very awkward place for absolute gravity. The other candidate sites that do not have facilities for absolute gravity yet are Vardö (Norway) and Visby (Sweden).

Finally, since funds for station construction are always limited, it is important to know which stations are available right know (Figure 6).

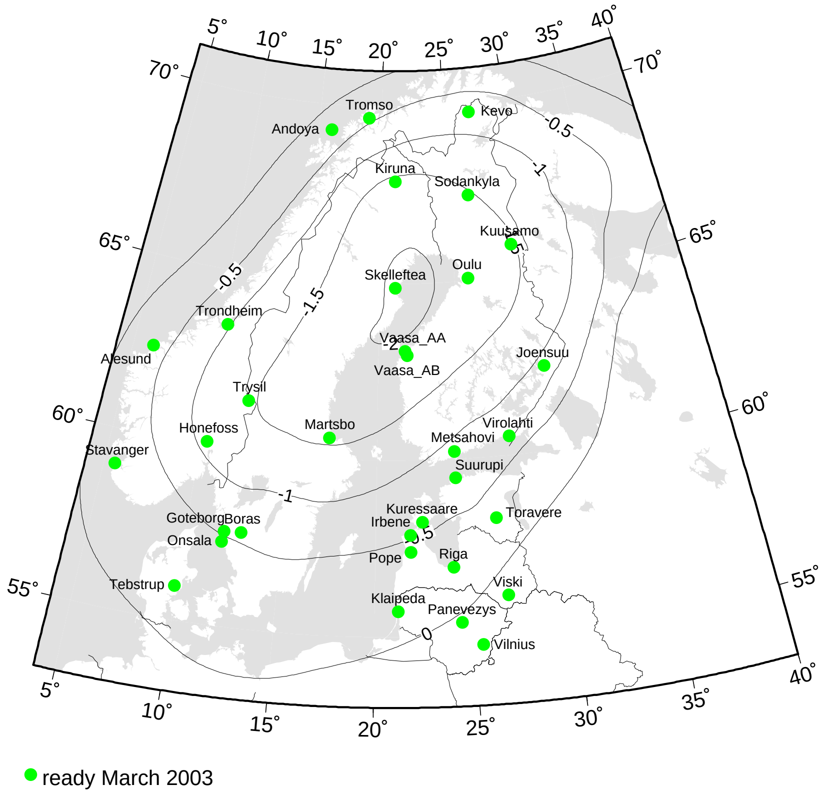


**Figure 6**. Stations of Figure 1 that are ready for absolute gravity measurements now. In addition, Kramfors, Östersund, and Vågstranda are in various stages of preparation.

## 5. Station choice and plan for 2003; underlying long-term plan

In 2003 we have a large total capacity because of the BKG engagement: about 30 station occupations in all. I believe that we should take advantage of this and observe correspondingly a large number of stations, even if it is not certain that they can be maintained with a high repetition rate in the future. Optimism here might in part be self-fulfilling since it may generate support to keep up the work, i.e., through an additional Nordic absolute meter. The bottleneck for 2003 is then the number of stations that are ready for absolute observations. At the same time we must take care that the stations observed form a useful set for the future in both cases, (i) if resources will allow to keep up a large number of occupations and (ii) if from 2004 on the resources will be limited to the 20-odd occupations by IfE and FGI.

The Appendix presents a somewhat meandering discussion of station distribution and repeat rate requirements. From it we make the preliminary propositions

(1) repeats will be primarily annual, which means 10-12 stations for both IfE and FGI (FGI in Finland). (With semiannual repeats the numbers would have to be halved.)
(2) stations should cover as large a range of PGR rates as possible (note that the curve of zero gravity rate in the figures corresponds to vertical velocity –1.2 mm/yr relative to MSL)
(3) existing long absolute and relative gravity records should be continued
(4) for sites that are new for gravity, permanent GPS is a near-must
(5) keeping up the 8 old absolute stations in Sweden and Norway measured with FG5s, and adding to them stations from the 63°N uplift line will nearly exhaust the annual repeat capacity

Further standpoints

(6) absolute meters will be compared primarily by simultaneous measurements in laboratories and not by double measurements of field sites
(7) it is expected that the national institutions want to participate in the ECGN, and will put a priority on constructing absolute-gravity facilities at ECGN candidate sites. This plan should take advantage of that.
(8) there is a preliminary engagement by the FGI to provide absolute gravity for Baltic ECGN sites

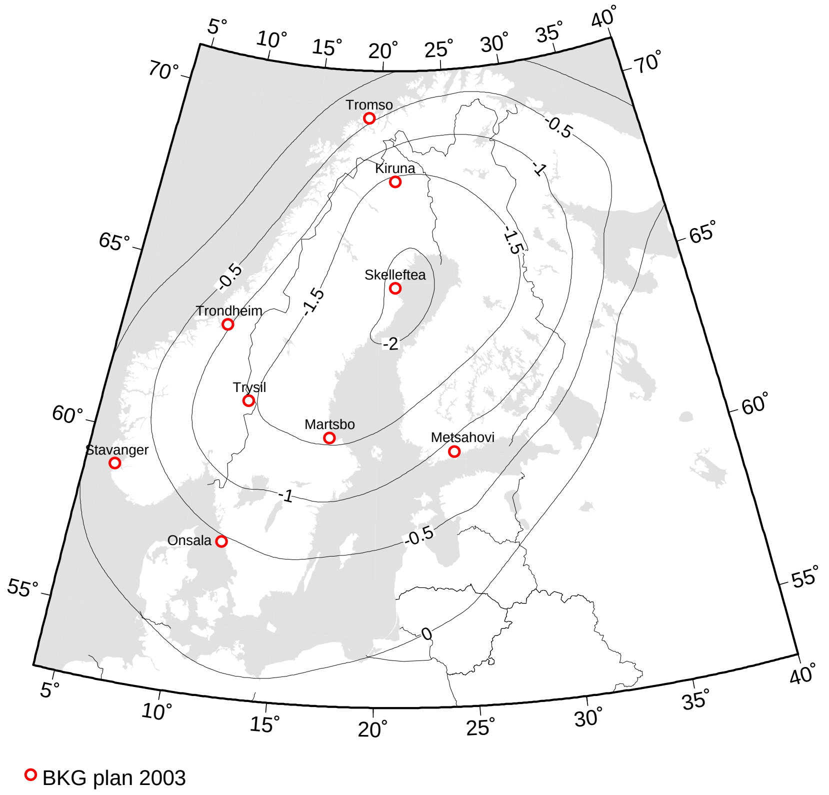


**Figure 7**. BKG plan in 2003 as far as I know.

The BKG plan for 2003 (above) is largely based on previous agreements and for the purposes of this document it is taken for granted. The FGI plan for 2003 (below) concentrates on stations in Finland as far as PGR work is concerned. Stations in Estonia and Latvia are reference sites of national gravity networks.

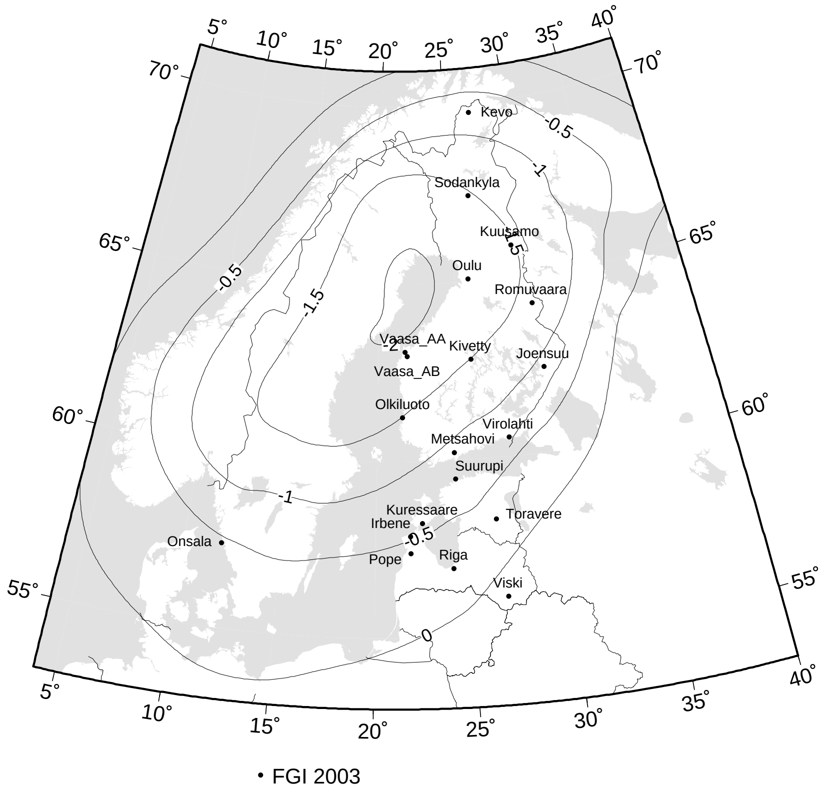


**Figure 8**. Preliminary FGI plan for 2003, “optimistic”. Probably not all three unprepared stations (Olkiluoto, Kivetty, Romuvaara) in Finland can be constructed in time, and on the other hand some intercomparison etc. sites could be added abroad. The sites in Estonia and in Latvia belong to a different project.

Figure 9 in the “Incomplete draft plan…” showed a version for the IfE 2003 campaign where most measurements overlapped with BKG and FGI, simply because there were not enough new stations to be occupied. Figure 9 in this version takes the opposite view and lists about 10 useful additions to the 2003 BKG and FGI programs, without regard whether the stations already have absolute gravity facilities or not.

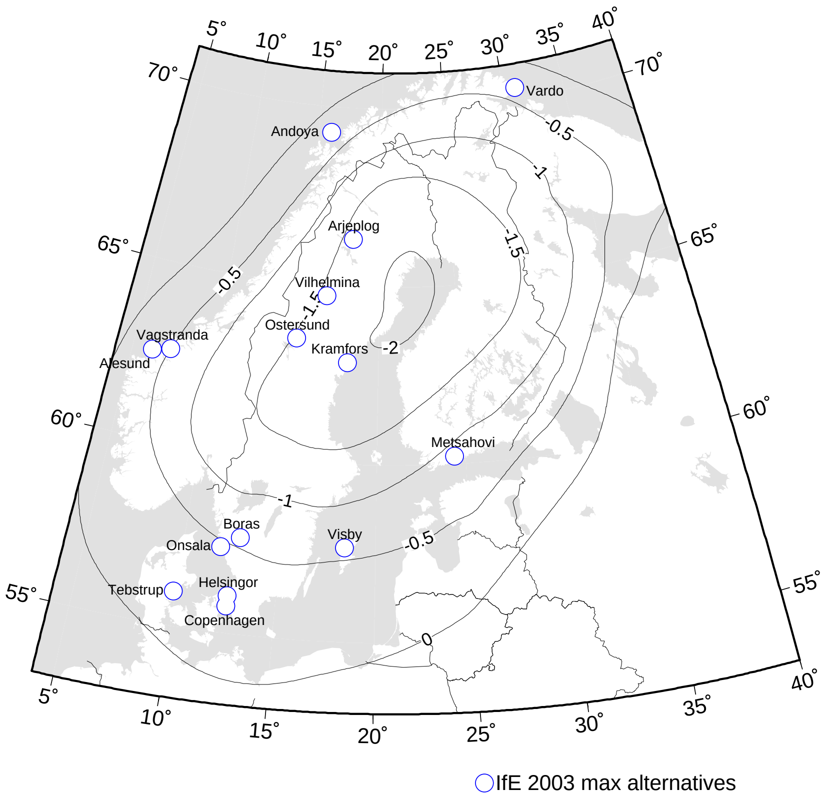


**Figure 9**. The maximum set for "new" sites for the IfE 2003 campaign, plus the two indispensable comparison stations (Metsähovi, Onsala). More information in Table 1. Which ones can actually be observed is discussed in the sequel.

**Table 1.** The maximum set of "new"sites for the IfE 2003 campaign. Those which already are prepared for absolute gravity are marked with x in the first column.

| | **Site name** | **Description, comments, questions** |
|---|---|---|
| x | Copenhagen | Could be the starting point of a SSW-NNE traverse over the uplift area. Stability relative to permanent GPS 10 km away? |
| x | Helsingör | IfE 1986 station, 56ºN station; 56ºN will be measured in 2003. No permanent GPS |
| x | Tebstrup | IfE 1986 station, 56ºN station; 56ºN will be measured in 2003. No permanent GPS |
| x | Borås | Can repeated absolute-gravity be expected to provide light on the discrepancy in GPS rates between Borås and Onsala? Metrology site but that is possibly beyond the scope of this plan. |
| | Visby | ECGN candidate and TG site. Will Lantmäteriet propose it for the ECGN? Can some existing construction be used for absolute gravity, or a pier/station built already in 2003? For geodynamics, would fill a gap over the Baltic proper. |
| | Kramfors | 63ºN line, will have a pier and permanent GPS, but not necessarily a building in time for the 2003 campaign. In this case, FGI has promised to stand in for 2003. |
| | Östersund | Geographically near 63ºN line, alternative to ECGN candidate Vilhelmina, and geodynamically the better site. Building plans for 2003 |
| | Vilhelmina | Alternative to Östersund, ECGN candidate because belongs to EPN, but unfortunately a bad site for absolute gravity; it would be far from the GPS. Seems that the EPN membership cannot be transferred to a better site. Will Lantmäteriet propose it? |
| | Arjeplog | Would fill a gap if Östersund instead of Vilhelmina is adopted. Must probably be given up anyway. |
| | Vågstranda | End point of 63ºN line, may have a pier but not necessarily a building and most likely not a permanent GPS in time for the 2003 campaign. Compare with Kramfors. |
| x | Ålesund | Has pier and permanent GPS and TG, but very close to Vågstranda. Could be parallel with but not substitute to Vågstranda. Pier reported difficult to access, may be moved. |
| x | Andöya | Has pier, TG and tandem permanent GPS. ESEAS-RI site. But is very close to Tromsö. |
| | Vardö | ECGN candidate and TG site. Will the Norwegian Mapping Authority propose it for the ECGN? Can some existing construction be used for absolute gravity, or a pier/station be built already in 2003? Could be the end point of a SSW-NNE traverse over the uplift area. |

Table 1 has 13 sites, and even after Arjeplog and either Vilhelmina or Östersund are removed, there is still too many. Now, how keen will the Nordic institutions be on getting sites into the ECGN? And even if they are interested, are there funds available for 2003?

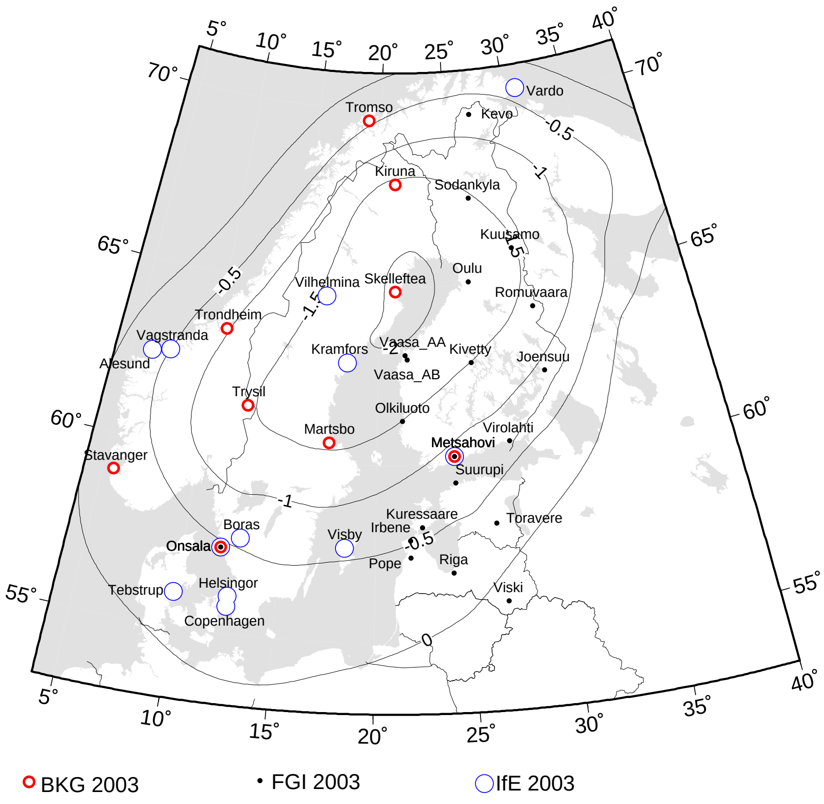


**Figure 10**. An optimistic plan for the 2003 season, assuming ECGN support from the institutions and maximal station construction effort: Kramfors, Vågstranda, Visby and Vardö, and either Vilhelmina or Östersund (alternatives, only the former is shown.) One or two intercomparison sites might be added.

In view of the multiple uncertainties that still prevail, I provide two "sample plans" for 2003; a number of intermediate versions can be thought of as well. Figure 10 shows a very optimistic plan where we are able to construct well-nigh all stations that we are interested in. Figure 11 shows a fallback version where only two stations have ben constructed.

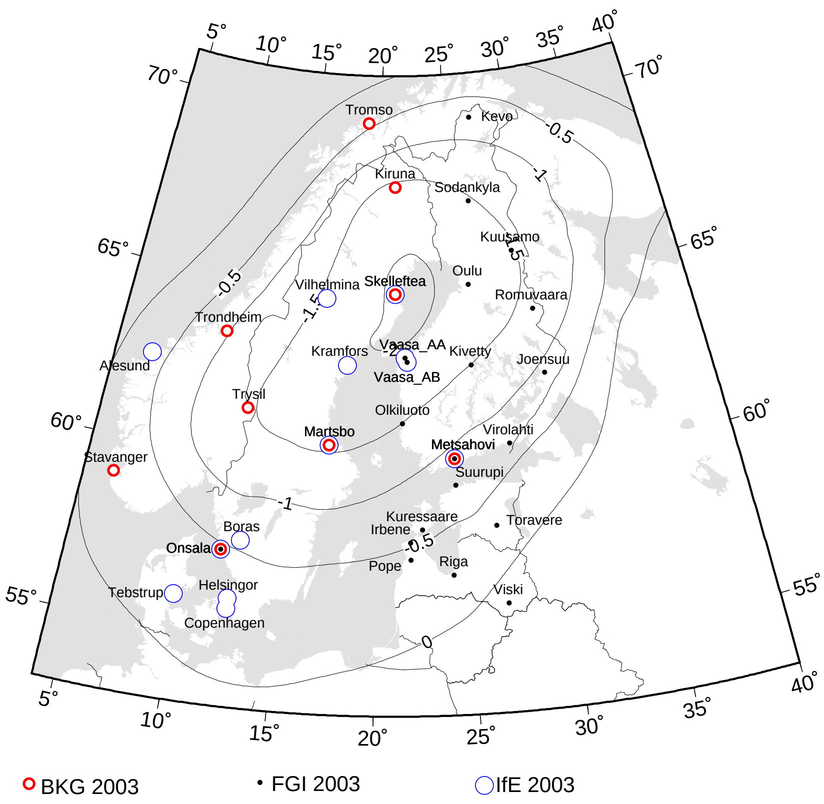


**Figure 11**. A fallback plan for the 2003 season, assuming minimal station construction, i.e., Kramfors and either Vilhelmina or Östersund (alternatives, only the former is shown.). The IfE effort is then invested on observing existing sites, largely in parallel with BKG and FGI. There is no hidden wisdom in this particular choice of such old sites.

A long-term plan that could be thought to underlie Figures 10 and 11 is shown in Figure 12. But we do not need to fix it at this stage: after experience and results from the 2003 campaign many things can revised.

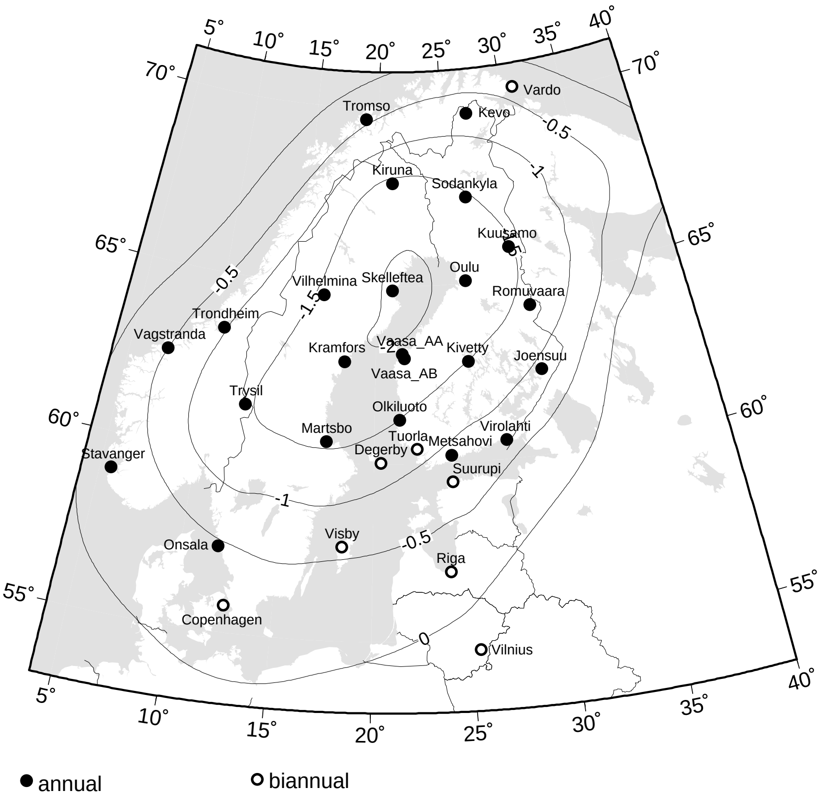


**Figure 12**. One possible repeat plan, assuming that the resources will come solely from the IfE and FGI projects and that the ECGN will be supported. Note that the skeleton consists of an E–W and a NNE–SSW traverse across the uplift area. In addition, there is the FGI support of potential Baltic ECGN candidates.

There are not enough resources to keep up annual repeats at all sites. In the map, most "new" sites are repeated biannually only. This must be questioned; should not new sites with short histories be sampled more often than old sites that already have long histories to fall back on?. and the southern part of the net has fewer annual repeats.

## 6. Practical tasks

Urgently

(i) construct sites at Kramfors and Vågstranda
(ii) clarify the standpoint of the Nordic institutions on ECGN
(iii) in the positive case, find out whether stations can be equipped for absolute gravity already for 2003
(iv) review possibilities to get hydrological data from or near candidate sites
(v) absolute teams should start coordinating instrument comparisons and campaign timing
(vi) perform the 2003 campaign

## 7. References

Sorry, I did not have time to compile them.

## Appendix: Viewpoints on repeat rate and on the distribution of the stations

The purpose is to have a dataset that maps the gravity change due to the postglacial rebound (PGR). The optimum then would be to cover the whole area with absolute gravity at the permanent GPS stations, and to have near-continuous measurements on them. Obviously, this cannot be achieved. Should we then have just a few stations and repeat them very often (more than once a year), or many stations and settle for fewer measurements? Some viewpoints follow, not all of them useful for the present task:

(a) whatever the relation between the rebound rate (vertical velocity) and gravity change turns out to be, they are bound to be highly correlated. Thus in view of the good geographic coverage by permanent GPS (by other techniques, too), we do not need to remap the uplift in detail using repeated absolute gravity. With a different wording: in any inversion both the gravity and GPS datasets can be used, therefore the gravity set alone does no need to contain the whole geographical info.

(b) a detour: the argument above can be used the other way around, to emphasize the importance of maintaining long-standing gravity series (the 63°N line), and their usefulness for PGR studies even when they are not co-located with permanent GPS.

(c) such cases are however an exception: the necessarily sparser absolute gravity dataset must at the vast majority of stations be co-located with permanent GPS, for mutual checking and corroboration of the results (measurement errors, non-PGR signals etc.)

(d) the gravity set should cover the whole range of PGR rates from the maximum to zero (preferably even below); a very high concentration of stations at the maximum does not seem useful

(e) it would be useful to do simulations for suitable target functions in PGR research, using the terrestrial data sets, with different sampling characteristics. (Such simulations have been performed for, e.g., the recovery of Earth rheology through GRACE observations of PGR).

(f) however, within the standard modelling of the PGR, using Maxwell rheology of the mantle, chemical boundaries at the density discontinuities at 420 and 670 km and seismically deduced values for parameters like the bulk modulus, there is apparently no escape from the ratio of about -1/6.5 µgal gravity change per mm of uplift

(g) within this kind of modelling, repeated absolute gravity will look exactly like campaign-style GPS; at best like GPS without the inherent reference frame problems of the genuine stuff

(h) and thus will turn out to be pretty superfluous in an area covered by permanent GPS

(i) so a useful simulation should probably assume that the relation between gravity and vertical rate needs to be determined and optimise this determination starting from signal and noise characteristics

(j) let us take here only take a brief look at them to outline some possible lines of thought

(k) in first approximation, gravity measurement error $\sigma$ may be assumed to be non-correlated between campaigns and then the standard error $\sigma_k$ (one-sigma) of the linear gravity rate $\dot{g}$, determined from $n$ equally spaced measurements covering a total time span of $T$ years, is well-known to be
$$\sigma_k = \frac{\sigma}{T}\sqrt{\frac{12(n-1)}{n(n+1)}}$$

(l) a sample table

| Time span years | Number of measurements | Measurement error, µgal | Error in $\dot{g}$ , µgal/yr |
|---|---|---|---|
| $T$ | $n$ | $\sigma$ | $\sigma_k$ |
| 5 | 3 | 2 | 0.57 |
| 5 | 6 | 2 | 0.48 |
| 5 | 11 | 2 | 0.38 |

(m) so it seems that there is little gain in $\sigma_k$ going from annual ($\sigma_k$ = 0.48) to semiannual ($\sigma_k$ =0.38) measurements

(n) one might even claim that it is better use the effort to observe another site annually instead, and to get an independent $\dot{g}$ with independent $\sigma_k$ = 0.48, and presumably another independent vertical rate as well

(o) however, not only measurement error, but the characteristics of the PGR signal and of the non-PGR signals in gravity and vertical velocity are relevant, too

(p) the PGR gravity and velocity signal are now, 10000 years after deglaciation, practically constant in a given place and vary very smoothly with place

(q) the GPS datasets so far seem to constrain neotectonic motion to very low levels

(r) both gravity and GPS sense global and regional mass redistribution signals (oceans, air mass, hydrology). After the routine corrections have been made the residual signals in the observations are to first approximation seasonal but a lot of interannual variation remains, too

(s) these signals are mostly regionally coherent for GPS and satellite gravity

(t) to the extent that the terrestrial gravity signal is due to loading, it is mostly regionally coherent, too

(u) a useful rule of thumb is that a regional load of 10 hPa (i.e. of 0.1 m of water) produces a vertical deformation of 3…4 mm and through it about 1 µgal in surface gravity (Newtonian part excluded)

(v) there is one particular signal in the terrestrial gravity, the Newtonian attraction from the near field variation in density (mostly through hydrology) that is shared by neither GPS nor satellite gravity
(w) while the density variations (subsurface water, surface snow) that cause it are regionally coherent as seen "from afar" (and the regional average is sensed by satellite gravity), their small-scale structure, and their local geometry relative to the gravity sensor make the gravity variation quite unpredictable from place to place
(x) one can at most hope to have the same sign at all sites (and even this is only true as long they all are above ground…)
(y) until recently, we believed to be relatively immune towards variation in subsurface water, as the majority of the sites are on crystalline bedrock
(z) the idea was that gravity effects would then be mostly due to the water in the sediment cover, in principle lateral to the gravity sensor but because of the topography in fact below it (many of the stations are on hills of some kind)
(aa) model calculations show that even such "lateral" effects can be surprisingly large, 20…30 percent and more of the corresponding Bouguer plate
(bb) things have recently turned out to worse still: the SG in Metsähovi on crystalline bedrock and relatively flat topography with very thin sediment cover shows gravity variations of 6 µgal p-p, which seem to come from water in the fractured bedrock
(cc) now the problem with this type of groundwater effect is that it is difficult to calculate the gravity variation even if you have the water record. Which coefficient to apply? In Metsähovi it was determined from the SG record and turned out to be 2.7 µgal/m, corresponding formally to an effective yield of 6%. How to get such a figure a-priori? Cf. the experience at Wettzell, too, where out of three wells, only one provided an explanation to observed gravity, and of course had to be calibrated against the gravity record.
(dd) here I cannot resist the pun that instead of crystalline bedrock, we might be better off on a laterally homogeneous sand aquifer in flat terrain, where the hydrological properties can be reliably determined from soil samples and the gravity integrated using the simple Bouguer model (there is a flaw in this reasoning but I will not go into it)
(ee) now suppose that we install a groundwater well at all absolute sites and get data the year around, not only when absolute gravity measurements are performed. We still must accumulate a lot of gravity data in order to determine the relationship between gravity and well level
(ff) (and we could have bad luck all the same and get a well like the two out of three in Wettzell)
(gg) the conclusion would be that given the spatially smooth PGR signals in gravity and velocity, and the spatially correlated non-PGR signals, plus the difficult-to-grasp local hydrological signal, it would be best to concentrate on less stations and denser sampling in time
(hh) in fact this line of thought seems to lead inevitably towards at least semiannual sampling, in order to get a grip on the seasonal variation in gravity, whether the comes from local hydrology or anything else
(ii) however, there are many practical objections to such a scheme
(jj) the absolute gravimeters are involved in several projects, and it would be difficult to "freeze" two observation periods each year for a single project, for several years in a row
(kk) one observation period would inevitably be in the winter, which would be quite difficult for transport and measurements on some stations, and would increase campaign costs in any case
(ll) additional environment observations (distribution of near-field snow cover) would be required (as well as dropping the snow from the roof of the hut before starting but that's a minor job)
(mm) and for interannual variations the dense sampling does not help much, only increased time span does
(nn) but possibly we should keep our minds open about this