BIFROST Project: Horizontal and Vertical Crustal Motion in Fennoscandia from 1500 days of GPS observations

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Abstract

This presentation compares results from continuous GPS observations in Fennoscandia and neighbour regions with other types of postglacial rebound related data. Vertical movements are compared to tide gauge and precise levelling. Baseline length changes are compared with a visco-elastic model. In the course of the data preparation we carefully examine reference frame issues. In post-processing stage we obtain refined rates (reduced by a best-fitting common mode) by means of Empirical Orthogonal Functions constructed from the motion residuals of neighbour stations.

Our results seem to indicate high rates in the centre of the uplift area—so high that we suspect a large bias. A likely explanation is the still short duration of the experiment compared to the original plan of 10 years. Also, during the first stages, changes of antenna characterstics may have had a large influence. We characterize these results as highly preliminary.

Horizontal motion can be inferred from baseline length changes with the advantage that this parameter is invariant under rotation and translation. Also, radome issues affect the horizontal components less than the vertical. Using only the swedish stations we obtain a pattern of unilateral extension, indicating that horizontal crustal shear on a continent-wide scale is an order of magnitude less important than postglacial rebound.

Background

The BIFROST project has been described earlier (BIFROST, 1996; Scherneck et al., 1998). In short, we use continuous GPS observations obtained at the permanent stations of the SWEPOS network in Sweden. In addition we incorporate observations from the equivalent network in Finland, FinnRef (Koivula et al., this volume). But, due to a different deployment schedule, part of the Finnish stations have been online shorter than 1500 days by varying amounts. Observations at number of IGS stations in Europe are used together with ITRF position and velocity information to map the regional positions into a well controlled geocentric reference frame.

Data analysis

Station positions in this presentation have been obtained with the GIPSY programme (Lichten and Border, 1987; Webb and Zumberge, 1993) using a nonfiducial strategy (Heflin et al., 1992). Bifrost solutions start in August 1993. Since then a number of versions of the reference frame have been issued: ITRF92, ITRF93, and ITRF94 (Boucher et al., 1996). Most recently, in conjunction with a transition to using JPL nonfiducial orbits we have used a JPL reference frame solution (Heflin, 1997; Heflin et al., 1992) that we will call Hef97 henceforth.

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The nonfiducial positions are mapped into the most recent reference frame evaluated at the actual date using reference site positions and velocities. The position evolution thus obtained is dominated by the tectonic plate motion with respect to a no-net-rotation origin. Our objective, however, is to discriminate deformation in the plate interior.

While station positions can readily be mapped into an arbitrary reference frame using a seven parameter transformation, we need to remember that the positions may contain systematic errors due to orbit errors. Some of these errors have very-long time behaviour and may be related to e.g. slow migrations of the orbit centre with respect to the reference frame origin. The accuracies of orbits and tracking station positions evolve by mutually gaining from each other. Moreover, positions that are computed with orbits that themselves refer to, say, ITRF92 but are mapped into Hef97 obtain an inconsistency.

Therefore, we need to compensate for the relative translations and rotations between individual issues of the frames. At some stations, Wettzell and Onsala being good examples, the reference velocities differ significantly. Anticipating that reference information becomes more certain as the data base at the IGS processing centres grows, we decided to use the most recently available ITRF (incl. Hef) and account for the interframe discrepancies in the post-processing stage.

We compute small rotations and translations using the catalogue velocities at all GPS stations that contributed to the respective ITRF's. The position of each station relative to its starting position is then corrected by the inverse of these frame motions. (The effect enters with a negative sign as it propagates via the satellites.)

The positions so corrected are once more reduced by the motion of a rigid frame that travels with the subset of those IGS stations the observations at which have been used in the Bifrost solutions. This frame will be called ARF (accompanying rigid frame). For this we use the most recent reference frame. There are two options, either to use a six parameter rotation and translation mapping or a three parameter rotation-only mapping. It can be shown that the latter case the ARF rotates around a fixed geocentre whereas in the former case the ARF is free to move vertically. The vertical motion of the regional sites is then reckoned relative to this motion which might pick up spurious tilts or other vertical motion which might be erroneous or even part of the signal we aim at. For that reason, the three-parameter rotation-only ARF would be preferable; it relies implicitly on the geocenter as derived from all Hef97 GPS stations world-wide.

In either case we obtain a mode of motion of the network that is deformation dominated. (It would also be possible to subtract a field that yields no-net motion at these sites, but in the present way we obtain Bifrost descrepancies with respect to the “official” reference information site by site.

If a station (Matera) is not on the same tectonic plate as the others we reduce its catalogue velocity with the Nuvel-1a (DeMets et al., 1994) relative motion.

Rates and refined rates

Least-squares adjustment of the single-site position time-series fits a rate that is assumed to be constant throughout the length of the time-series and generalized seasonal variations $s_j(t)$, individually for each spatial component. In addition, at each known instance when changes were made to the antenna (exchange of radomes), a bias term $H(t-t_j)$ (Heaviside's distribution) is introduced (and of course at $t_1 = 0$ to adjust to the reference position). We also condidered side-effects due to changing a large number of antennas possibly affecting sites where conditions were kept constant.

$$x_{kt} = \sum_j p_{kj}\ s_j(t) + a_k\ t + \sum_j b_{kj}\ H(t-t_j)$$

or more symbolically

$$\mathbf{x} = \mathbf{Y}\mathbf{p}$$

for each of the spatial components $k = X, Y, Z$. In the above we have weighted the data with the formal sigmas obtained from the GIPSY solution. There are M parameters and N data samples.

Inversion uses Generalized Inverse (GI) method of Lanczos (Aki and Richards, 1980, Chap. 12.3) with M eigenvalues λ, dataspace eigenvectors $\mathbf{v}$ and modelspace eigenvectors $\mathbf{u}$.

$$\begin{aligned} \mathbf{Y}\mathbf{u} &= \lambda\mathbf{v} \\ \mathbf{Y}^\top\mathbf{v} &= \lambda\mathbf{u} \end{aligned}$$

We delete eigenvalues by a magnitude ratio criterion 1:10^{-8}. At this point there is only little difference to ordinary weighted least-squares; e.g. the GI manages singular matrices as due to coinciding bias events, that happen frequently when baseline vectors are processed instead of single-site positions. The inversion is given by

$$\mathbf{p} = \mathbf{V \Lambda U}^{\top} \mathbf{x}$$

Empirical Orthogonal Functions

In our analysis for refined rates we try to remove a common mode signal from the position time-series. The common mode is determined in a separate stage of the least-squares inversion

$$x_{kt} = \sum_j p_{kj}\ s_j(t) + p_k^{pl}\ s_{kt}^{pl} + a_k\ t + \sum_j b_{kj}\ H(t - t_j) + \sum_j q_{kj}\ r_{kt}^j$$

where the residuals of station j in the previous stage, r_{kt}^j, are “recycled”. We have also added an atmospheric pressure loading time-series s^{pl} to the signal model.

A set of Empirical Orthogonal Functions (EOF) are constructed from r_{kt}. If only these were present in the signal model, we would retain just one (the greatest) eigenvalue. In the mixed case where EOF’s are constructed from only a subset of the components of the signal model, the work amounts to identifying what the eigenvectors represent. Let p_1 to p_K be the parameters of the recycled residuals. In parameter space, the common mode is associated with an eigenvector having elements 1 to K of the same sign and similar magnitude, and K+1 to M much smaller elements. The eigenvalues to be deleted have equally low magnitude in elements K+1 to M, but other (mixed-sign) combinations of elements 1 to K.

In data space, the eigenvectors representative of the residuals are characterized as being similar to white noise. The common mode is easily singled out as it pertains to the largest eigenvalue, while the others can be searched with a white-noise detection method. We propose application of Structure Function methodology (Davis et al., 1994), searching for the K-1 eigenvectors with the smallest power index to remove them from the GI. This can be automated.

The common mode is obtained from

$$\sum_j q_{kj}\ r_{kt}^j$$

It is seen to pick up features at all time scales. The weighted residual has a normalized χ^2 typically about 50% of the case without EOF. The solutions for the rates are only moderately affected.

Inspection of joint confidence limits for Skellefteå as an example shows high correlation between the estimates of rates and offsets; however, the 95% confidence ellipse indicates a rate between 16.7 to 17.1 mm/yr (cf Fig. 1).

Vertical rates

We show Bifrost vertical rates versus results from tide gauges and precise levelling (Ekman, 1998, this issue). The steepness of the regression line between both data types is indicative of the geoid rebound while the zero intercept of the Bifrost results points out the negative of a general sea level change.

Our results (Fig. 2) show high inclination of the regression line. A geoid rebound of 55% of the vertical rate appears unrealistic to suggest.

The large correlation between offsets and rates suggests that the rates obtained in BIFROST may be biased. Therefore, rate results should be considered preliminary. Since all antenna changes occurred at approximately the same time, and since the rates correlate with the height of the jumps, an amplification of the rates can be expected rather than a constant offset. A dichotomy between stations that underwent changes and those that did not is difficult to establish since all stations with high rates and low variances are SWEPOS stations, i.e. have had their radomes exchanged.

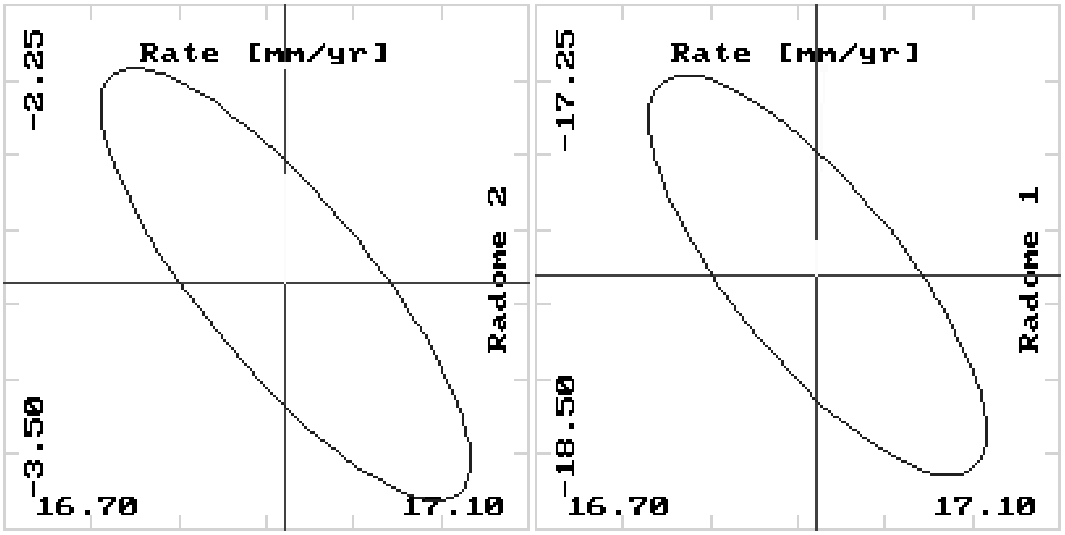

Figure 1: Joint confidence limits (95%) for rates and offsets at Skellefteå

Horizontal motion and deformation style

Since BIFROST baselines are short compared to the earth radius, baselines length is dominated by horizontal movements. The length component has the advantage that it is invariant under rotation. Baseline length time series have been used to fit rates. These rates are compared with contemporary baseline rates from the postglacial rebound model of Mitrovica et al. (1994).

We have used only those baselines where there have been more than 800 (500) daily solutions.

A scatter diagram of observations versus model (Fig. 3) shows a noticeable degree of correlation between both (χ^2/ν = 57, ν = 165). Eliminating the GPS station SAAR improves the fit to within 5σ. Using the larger set with minimum 800 solutions containing 250 baselines gives χ^2/ν = 50, respectively χ^2/ν = 30 when SAAR is removed.

We suspect the anomalous motion at SAAR to relate to the fact that the antenna is not mounted on a standard SWEPOS pillar. The station operated by ESA has the antenna mounted on the roof of a building instead.

It is important to observe that the only set of baselines showing shortening involves the Wettzell station, and that this shortening is predicted by the model. If major zones of crustal shear were the dominating style of deformation, pairs of extending and shortening would be expected. If such a style exists, it is obviously hidden below the unilateral extensional style. Drawing a rose diagram with baseline deformation $\delta l/l$ shown along the azimuth of the baseline, using the unit circle's sectors III and IV to plot shortening, does not indicate a preferred direction.

After the model rates have been subtracted shortening baselines are found at preferred NE-SW azimuth. This is not expected from e.g. the European stress map (Müller et al., 1992) which for most of central Europe shows maximum compression along a NW-SE azimuth. In northern Europe, maximum stress directions scatter, which may be taken as yet another indication that surface extension in the course of the rebound is a prevailing feature.

At this point, however, it is important to point out that most of the baselines to Finland fall short of the 800 days threshold. In the future we expect a more homogeneous coverage of the whole area and perhaps more clear results as regards tectonic signatures.

Conclusions

The issues of reference frame and orbit which we encountered in the BIFROST work are considered to be cumbersome by us. An optimum strategy would deconstrain the site positions that

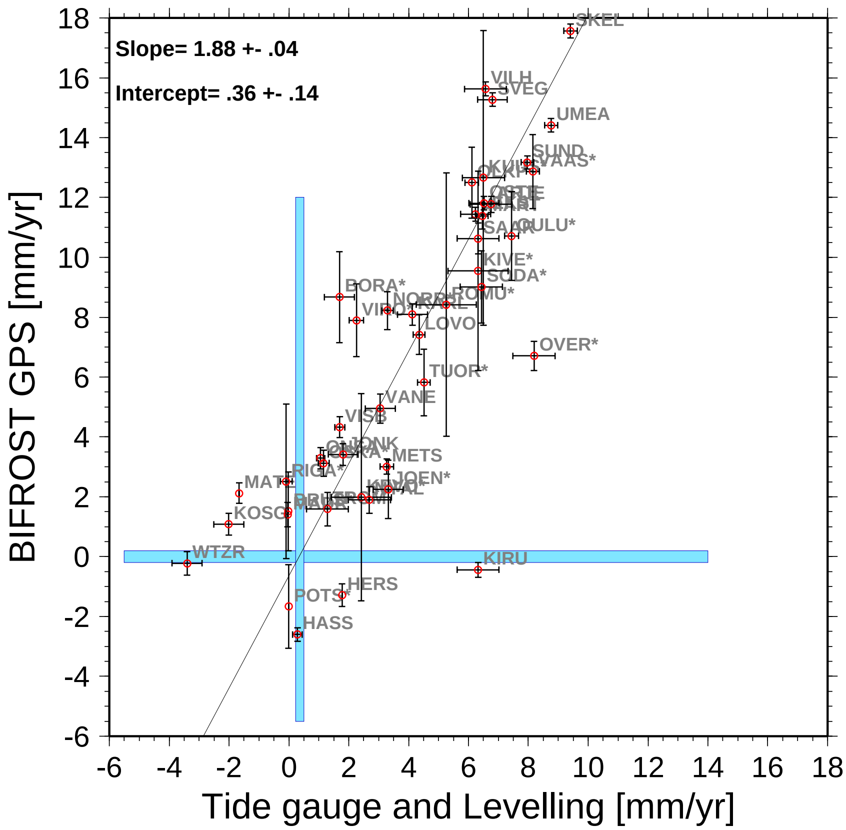

Figure 2: Bifrost GPS-determined rates versus tide gauge and precise levelling results.

were used in orbit determination and thus to compute a station position solution that is more fully internally consistent.

The high inclination of the regression line found by us between vertical motion observed with GPS versus mareographs, as shown in our figures, certainly has no justifyable physical interpretation as large geoidal rebound signature. We suggest instead that the GPS determined vertical rates are correlated with the estimated temporary offsets that had to be introduced in order to account for changes in the antenna characteristics in connection with changes of antenna radomes. As the BIFROST project is likely to continue for another five years, this bias will become smaller. And as more data are collected and analyzed undisturbed time-series will soon become long enough to provide reasonable confidence limits. Thus, the results presented here will have to be lookeded upon as preliminary. This uncertainty extends also to the zero intercept of the GPS-mareograph regression, which is indicative of a constant sea level rise in the region, and is one of the key quantities to be determined in BIFROST.

Horizontal components of GPS determined positions are to a lesser degree affected by antenna characteristics. The baseline length components draw from this advantage and in addition are invariant to reference frame rotations and translations. We are therefore more confident when interpreting the regression between observed and modelled baseline length variations. Our findings hint at a predominant style of extension and high correlation with the deformation pattern expected from postglacial rebound, including a near-unity slope of the regression. A clear anomaly has been found in one case. Considering that the monumentation of the particular site on top of a building is not complient with the SWEPOS standard, we tend to attribute the anomalous motion to local deformation external to the bedrock or possibly to effects from varying conditions for signal propagation including multipath. The exceptional case underlines the rule that SWEPOS observing stations appear to have good baserock coupling and undisrupted observing conditions

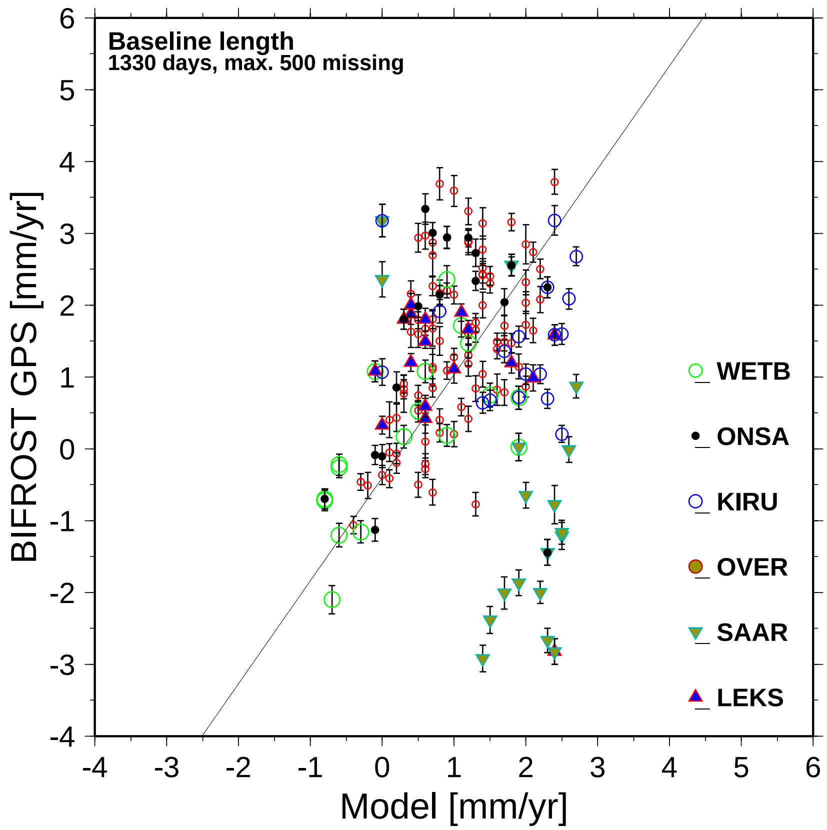

Figure 3: Baseline rates determined by Bifrost GPS compared to the rebound model of Mitrovica et al. (1995). Some baselines have been coded to emphasize particular stations. Noteworthy are WETB in the peripheral subsidence zone where shortening baselines are expected. SAAR is mounted on a building near Kiruna. LEKS has been subject to frequent monument monitoring and antenna remounting in its course.

in the horizontal components in particular.

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