Effects of intraplate deformations on fixing regional reference frames

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Abstract

The horizontal and vertical kinematics of Norway are determined on the basis of two repeated GPS campaigns for 24 points and a network of 9 permanent GPS sites. Comparing the horizontal velocities to NUVEL-1A-NNR predictions, good agreement is found for the north component, while there is a significant difference in the east component. For this component, a residual velocity of approximately 3 mm/yr towards west is found.

ETRS89 is realised using NUVEL-1A-NNR and thus, there is a secular horizontal motion of Norway with respect to EUREF89, the national realisation of ETRS89. Part of this secular motion is due to intraplate deformations with the main contribution in Norway being the horizontal motion due to postglacial rebound. Replacing the NUVEL-1A-NNR pole for the Eurasian plate with a new pole recommended in EUREF Resolution 2 of 2001 bears the danger of absorbing part of the postglacial signal in a new realisation of ETRS89.

1 Introduction

Geodetic reference systems are commonly realised by a set of points for which initial epoch coordinates and (optional) linear velocities are given (see, e.g Altamimi & Boucher, 2001). Consequently, for the analysis of space-geodetic observations from different epochs, a model for station motion is required, which includes geophysical models for processes affecting station position relative to the reference frame.

The presently used methodology for fixing reference frames causes problems in the geophysical interpretation of time series of station coordinates since parts of the surface motion due to a given geophysical process may be absorbed in the reference frame itself. As shown recently by Nocquet et al. (2001), particular care needs to be taken when fixing regional reference frames to the "stable" part of a tectonic plate, as the identification or selection of the "stable" part determines the relative station velocities with respect to the reference frame. Thus, a subsequent geophysical interpretation may be affect by the specific selection of the "stable" part.

In what follows we will first comment on the model widely used to account for station motion. We will then use the Norwegian national reference frame (see end of Section 2) and GPS data from Norwegian networks (see Section 3) to elucidate potential ambiguities in the geophysical interpretation of surface motion due to reference frame fixing (Section 4).

2 Comment on the station motion model

In the analysis of space geodetic observations, a model for the station movement is used, where the

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position of a point $x_i, i = 1, 2, 3$ is given by

$$x_i(t) = x_i^0 + v_i^0(t - t_0) + \sum_{j=1}^{N} g_i^j(t, \vec{x}^0) \qquad (1)$$

where t is the time, t_0 the origin of time, x_i^0 the point coordinates at time (or epoch) $t = t_0$, $v_i^0, i = 1, 2, 3$ is a constant, linear velocity of the point, and $g_i^j, i = 1, 2, 3$ are geophysical processes, which affect the point coordinates (see, e.g. McCarthy, 1996).

In analyses of space-geodetic observations taken at a fixed point, unknowns are often x_i^0 and v_i^0 while models are used to correct for geophysical processes thought to be known with sufficient accuracy.

For computation of time series of station coordinates for $t = t_l, l = 1, ..., N$, it is most common to analyse data of a full day and to use

$$x_i(t_l) = x_i^l + \sum_{j=1}^{N} g_i^j(t_l, \vec{x}^l) \qquad (2)$$

as model for the station coordinates, where the unknowns for each sample time t_l are x_i^l. The coordinates given in time series therefore are normally residuals with respect to the models used in the analysis and this has to be taken into account in the geophysical interpretation of the time series.

It is important that the geophysical processes in eqs. (1) and (2) do not contribute to a linear movement or a coordinate offset (see, e.g., the discussion of Earth tides and the pole tide in McCarthy, 1996). The necessity to elliminate constant and secular contributions from the models results in non-uniqueness in the practical use of the equations. Therefore, we choose to write eq. (1) as

$$x_i(t) = x_i^0 + \sum_{j=1}^{N} \tilde{g}_i^j(t) + \delta g_i(t) + \epsilon_i(t), \qquad (3)$$

where we have omitted to write that all terms on the right-hand side are dependent on position (i.e. on $\vec{x}$). $\tilde{g}_i^j$ are the complete coordinate variations due to all known geophysical processes including constant offsets and secular changes. δg represents the contribution of unmodelled geophysical processes. ϵ stands for the observation errors and errors due to other processes affecting the coordinates without actually corresponding to point movements. Eq. (3) can be written as

$$x_i(t) = x_i^0 + \sum_{j=1}^{N} \tilde{g}_i^j(t) + \tilde{v}_i^0 \cdot (t - t_0) + \delta\tilde{g}(t) + \tilde{\epsilon}(t). \qquad (4)$$

In eq. (4), $\tilde{v}_i^0$ is a residual linear velocity which absorbs all secular changes in δg_i and ϵ_i.

For the geophysical interpretation of geodetic time series describing station movements, it would be better to have access to $x_i(t_l)$ instead of x_i^l as defined in (2).

The IERS conventions (se McCarthy, 1996) give recommendations on how to model the geophysical processes in the space-geodetic analyses. The list includes

- Earth tide;
- ocean tidal loading;
- deformation due to polar movement;
- deformation due to atmospheric loading;
- post-glacial deformations;
- plate tectonics.

Not included are hydrological and cryospheric loading, deformation induced by sedimentation processes, deformation due to groundwater and oil/gas extraction, neo-tectonics. The boundary between what is recommended to be modelled and what not appears to be between known and unknown processes. Thus, the aim appears to be to create station coordinates that, after having removed all known variations, show the least variations over time. For geophysical interpretation, we are left with

$$x_i^l, \; l = 1, ..., N \qquad (5)$$

This cause a dilema for geophysical interpretation. In what follows, we will use plate tectonics and post-glacial rebound as an example. In Scandinavia, these two processes are the main contribution to secular changes in station coordinates with respect to a global reference frame.

The IERS conventions recommend to use the NUVEL-1A-NNR model to account for plate tectonic movements. This model gives the rotation vectors of the major (rigid) tectonic plates, which have been determined on the basis of geological evidence from the last several million years (DeMets et al., 1990, 1994). Comparison with geodetically determine velocities for the global geodetic networks show very good agreements in stable areas. It should, however, be mentioned that the extension and exact boundaries of the presumably large areas with signifcant horizontal deformation are not globally known (see, for example, Fig. 6 in Stein, 1993).

The IERS recommendation has also been taken up by EUREF in the realisation of the EUREF reference system. Consequently, the national geodetic authorities have based the realisation of EUREF in their countries on the use of NUVEL-1A-NNR (see for example Kristiansen & Harsson, 1999; Jivall & Lidberg, 2000).

The official Norwegian reference frame, which is called EUREF89, EUREF89 originates from the EUREF-NOR94 and EUREF-NOR95 campaigns (Kristiansen & Harsson, 1996, 1999). For these campaigns, observation time was 3 days for each point. Fixing the reference frame in ETRS89 was performed according to the recommendations of the EUREF Commission (Boucher, 1994). There, three steps are specified, namely (i) computation of point coordinates at t_c, the central epoch of the observations, in the nearest ITRF, (ii) transformation of coordinates to ETRS89 at central epoch, and (iii) referring the coordinates to initial epoch 1989.0. In step (iii),

$$X^E(89.0) = X^E(t_c) + \dot{X}^E \cdot (1989.0 - t_c) \quad (6)$$

is used, where X^E are the coordinates and $\dot{X}^E$ the station velocities in ETRS. In step (i), coordinates were computed in ITRF93. In step (ii), NUVEL-1A-NNR is used to account for the rigid tectonic motion of the European plate. Therefore, for stable parts, $\dot{X}^E = 0$ can be assumed according to Boucher & Altamimi (2001). Due to lack of a reliable model for postglacial rebound, no attempt was made to correct for intraplate motion in the fixing of EUREF89 in Norway. Thus, it was assumed that

$$X^E(89.0) = X^E(t_c) \quad (7)$$

where $t_c \approx 95.0$.

Below, we will discuss the consequences of the specific selection made for steps (ii) and (iii). Before that, in the next section, we give a brief account on the GPS data and analysis used to derive station velocities.

3 GPS observations and analysis

The Norwegian Mapping Authority operates a network of currently 15 continuous GPS (CGPS) stations to provide a national geodetic reference frame (see Figure 1). For 9 of these stations we have available observations from February 1997. The stations are equiped with dual frequency receivers and choke ring antennas. Data acquisition is done in near real time at the control center at Hønefoss.

Moreover, 119 so-called 4-D points[1] are established for repeated GPS campaigns. These points are equipped with permanent bolts. The bolts are threaded so that a GPS antenna can be screwed onto it and thereby a forced and repeatable centering is ensured. Inital epoch measurements were carried out on all points in the 1994, 1995, and 1996 campaigns. 24 points initally measured in 1994 were reoccupied in 1998. For these points, displacement vectors over a period of 4 years can be computed.

Both the data from the CGPS sites and the reoccupied campaigns have been analysed using precise point positioning with GIPSY/OASIS-II in a solution based on JPL non-fiducial orbits, clocks, and Earth rotation parametres. The non-fiducial coordinates are transformed to ITRF97 at central epoch. For the CGPS sites, velocity vectors are determined from a least squares fit of a straight

[1]The points are called 4-D points to emphasise the fourth dimension time in addition to the three spatial coordinates; that is, the 4-D points are intended for monitoring surface movements through repeated campagins.

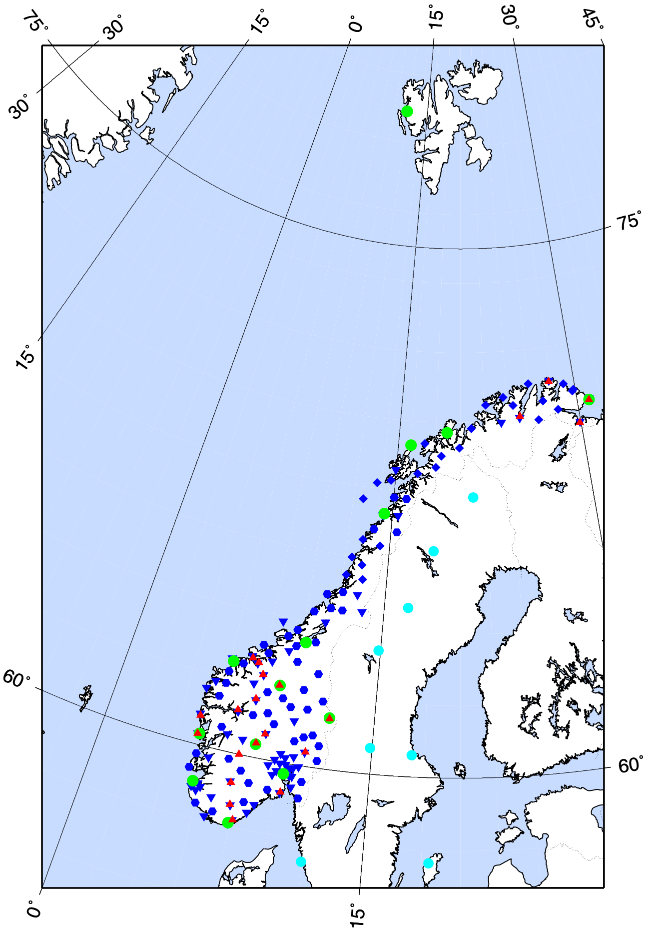

Figure 1: Permanent and episodic GPS sites in Norway.
Circles are CGPS sites. Triangles are 4-D points occupied both in 1994 and 1998. Other symbols represent 4-D points measured once in 1994, 1995 or 1996.

line to the coordinate time series starting at February 1997. For the 4-D points, velocities are determined from the displacement vectors between the two campaigns in 1994 and 1998.

4 Comparison of observed kinematic and models

In Fig. 2, we compare the horizontal velocities for the CGPS sites and the 4-D points given in ITRF97 to the predictions of NUVEL-1A-NNA. For the north component, the observed velocities are in good agreement with the model predictions. For the east component, however, we see a systematic difference with the observed velocities being of approximately 3 mm/yr less than the predicted ones.

It should be mentioned here that no difference is seen between the observed velocities from the CGPS and the campaign points. For the horizontal velocities, the repeated campaigns four years appart appear to give rather reliable results. But below we will see that this is not the case for vertical velocities.

The difference between the observed and predicted east velocities can be interpreted as a movement of Norway relative to NUVEL-1A-NNR. Using NUVEL-1A-NNR in referring coordinates from the observation epoch to EUREF89

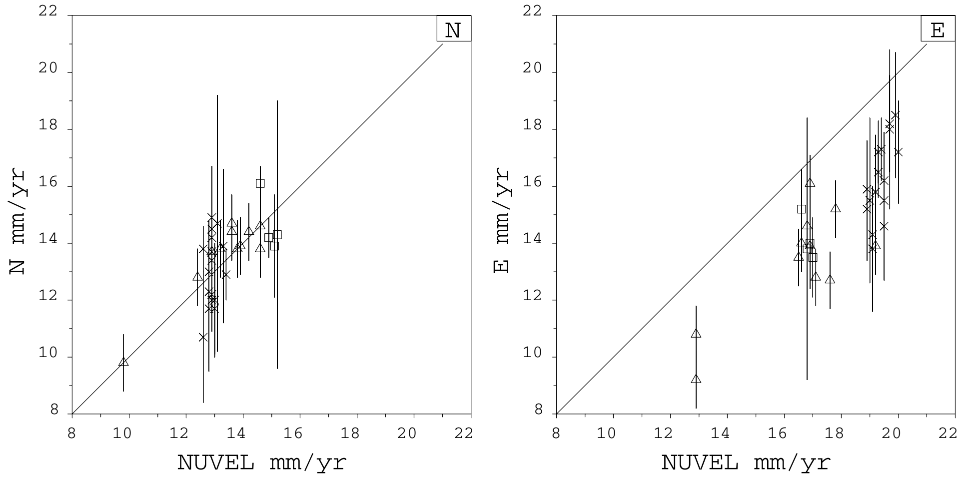

Figure 2: Comparision of observed and predicted horizontal velocities.
The diagrams show on the horizontal axes horizontal velocities predicted by NUVEL-1A-NNR and on the vertical axes observed velocities for the north (left diagram) and east component. Triangles: CGPS sites, cross: 4-D points in southern Norway; boxes: 4-D points in northern Norway.

in Norway thus results in an error δX_{East}

$$\delta X_{\mathrm{East}} = -3 \cdot (t - t_0^{\mathrm{effective}}) \quad (8)$$

where t is the time of measurement in years, δX_{East} i mm. $t_0^{\mathrm{effective}}$ is not 1989.0, the reference epoch but rather approximately 1994.6, the time when the observations for the realisation of EUREF89 were carried out. In the realisation of EUREF89, NUVEL-1A-NNR has been used to model the rigid tectonic motion of the European plate (Kristiansen & Harsson, 1999; Boucher & Altamimi, 2001) and for measurements prior to 1994.6 no error would be introduced.

We ask now whether the relative movement of Norway with respect to NUVEL-1A-NNR can be explained by horizontal motion due to post-glacial rebound. The horizontal post-glacial rebound signal (pgs) has been discussed in a sequence of papers over the last years (see, e.g. James & Morgan, 1990; Mitrovica et al., 1994; Milne et al., 1999) and despite some unresolved differences in the model predictions, the velocities are found to be of the order of a few mm/yr. Fig. 3 shows the horizontal velocities for a typical model (Milne et al., 1999).

In Fig. 4, the differences between the observed and NUVEL-1A-NNR predicted velocities (which we denote as *relative velocities* below) are compared to the pgs predictions of the model in Fig. 3. For the north component, no significant differences between the relative velocities and the pgs predictions are found. However, this is mainly due to the uncertainties in the observed relative velocities, which are larger than the predicted pgs signal. For the east component, the predicted pgs velocities are systematically smaller than the observed relative velocities. Thus, the geophysical post-glacial rebound model explains the west movement of Norway relative to NUVEL-1A-NNR only partly. Here we have to point out that geophysical models using other ice histories or viscosity profiles in the Earth's mantle predict larger or smaller velocities towards west (see e.g. Milne et al., 2001). Does this mean that the relative velocities can be used to distinguish between different geophysical models? Or are these relative velocities affected by secular movements of the reference frame?

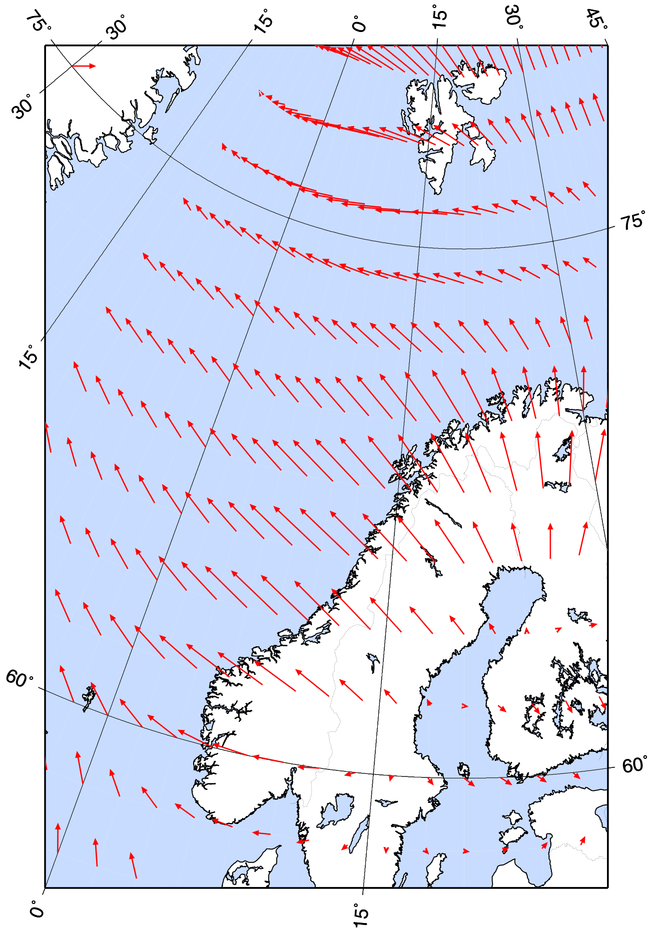

Figure 3: Predicted horizontal movement due to post-glacial rebound.
The model is from Milne et al. (1999). Arrows point in direction of movement. The scale is given by the arrow plotted at 30°W,75°N, which corresponds to 1 mm/year.

During the establishment of ITRF2000, Altamimi & Boucher (2001) (see also Boucher & Altamimi, 2001) determined transformation between ITRF2000 and ETRF89. Here it is important to remember that ETRS is defined as a reference system fixed to the stable part of the Eurasian plate[2]. The rotation of ETRF89 with respect to ITRF2001 therefore should be in agreement with the rotation given by NUVEL-1A-NNR for the Eurasian plate. However, Altamimi & Boucher (2001) find a rotation vector which is significantly different from the one in NUVEL-1A-NNR. For Norway, the difference between the ITRF2000 rotation and the NUVEL-1A-NNR rotation results in a nearly homogeneous horizontal velocity field of approximately 3 mm/yr towards north-west. This corresponds very well to the differences between observations and NUVEL-1A-NNR described above.

Boucher & Altamimi (2001) specify the routines for referring GPS results given in a ITRF at central epoch to ETRF89. For ITRF2000, they suggest to use the new ITRF2000 pole for the Eurasian plate instead of the NUVEL-1A-NNR pole. In Resolution 2 accepted at the eleventh EUREF meeting in Dubrovnik, May 2001[3],it is rec-

[2]see Resolution 1 of the EUREF meeting in Florence, 28 - 31 May 1990, available at http://www.euref-iag.org/resolutions.html#Florence.

[3]see http://www.euref-iag.org/resolutions.html#Dubrovnik.

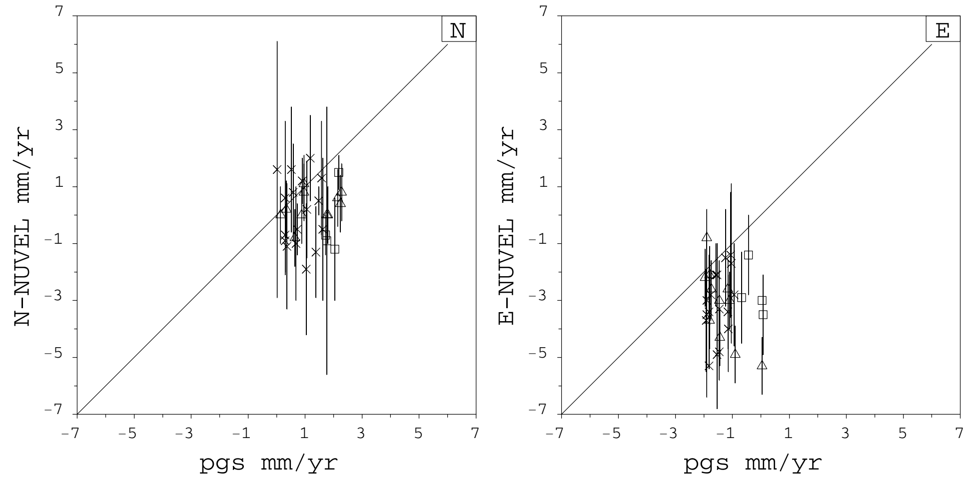

Figure 4: Residual horizontal velocities versus pgs predictions.
The diagrams show on the horizontal axes the horizontal movement due to post-glacial rebound predictions of the model given in Fig. 3. On the vertical axes, the differences between observed velocities and NUVEL-1A-NNR predictions are given. Left: north component; right: east component. Symbols are the same as in Fig. 2.

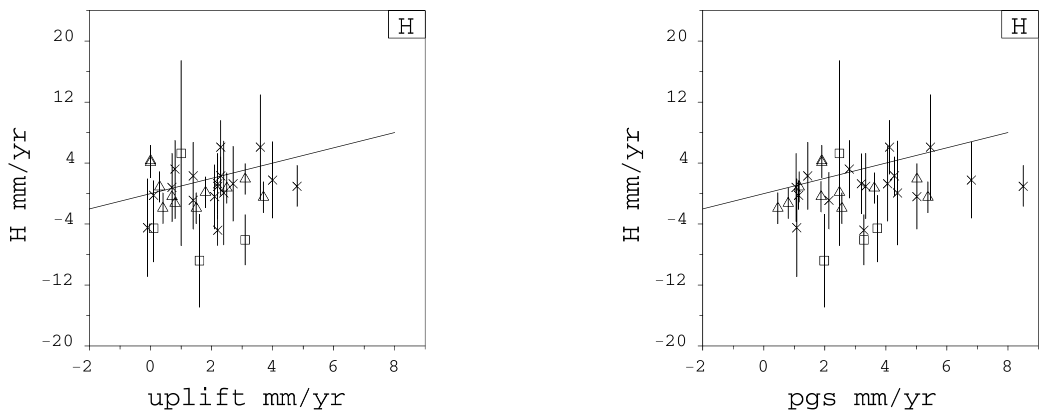

Figure 5: Comparison of GPS-determined vertical velocities with land uplift models.
Diagrams show on the vertical axes observed vertical velocities. The horizontal axes show the velocities computed from the emphirical modell (Danielsen, 1999, left diagram) and the geophysical model (Milne et al., 1999, right diagram). Please, note that the scale on the vertical axes is different from the one on the horizontal axes. Points with perfect agreement between models and observation lie on the line. Symbols are the same as in Figure 2.

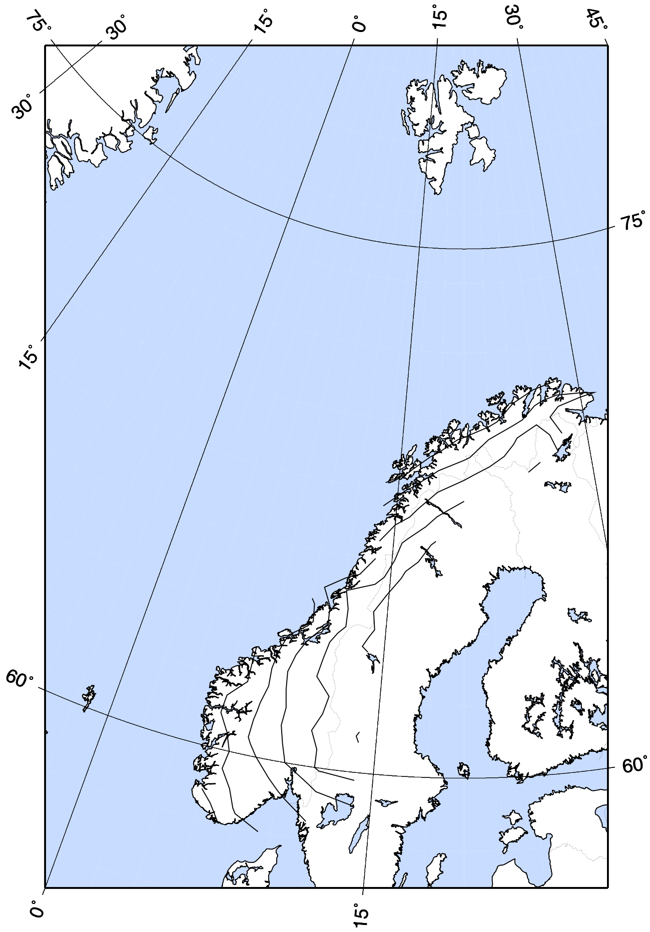

Figure 6: Vertical velocity predicted by the emphirical land uplift model.

The model is the emphirical model, which is the official land uplift model of the Geodetic Institute, Norway (Danielsen, 1999). Separation of isolines is 1 mm/yr.

ommended to replace the NUVEL-1A-NNR pole for the Eurasian plate through the new ITRF2000 pole. It is important to point out that Altamimi & Boucher (2001) used

$$\vec{V} = \vec{\omega} \times \vec{X} \tag{9}$$

to determine the rotation vector $\vec{\omega}$ for Europa on the basis of 19 selected ITRF stations with high geodetic quality. Station distribution is such that the new pole is more representative for western Europe than the whole Eurasian plate. For Norway, another point is even more important: it is possible that the station distribution has resulted in a large part of the horizontal movement due to postglacial rebound being absorbed in the rotation. It may be more appropriate to use

$$\vec{V} = \vec{\omega} \times \vec{X} + \gamma \vec{V}_{\rm pgs} \tag{10}$$

to determine a rotation pole for Europe, where $\vec{V}_{\rm pgs}$ is the horizontal velocity predicted by a geophysical postglacial model. γ is an unknown scale factor which is introduced to account for uncertainties in the model used.

In Figure 5, the observed vertical velocities are compared to two different models for vertical velocities. One model is the currently accepted model for land uplift of the Geodetic Institute, Norway. This model is an emphirical model determined on the basis of tide gauge data, precise levellings, and century-long observations of biological waterlevel indicators (Danielsen, 1999).

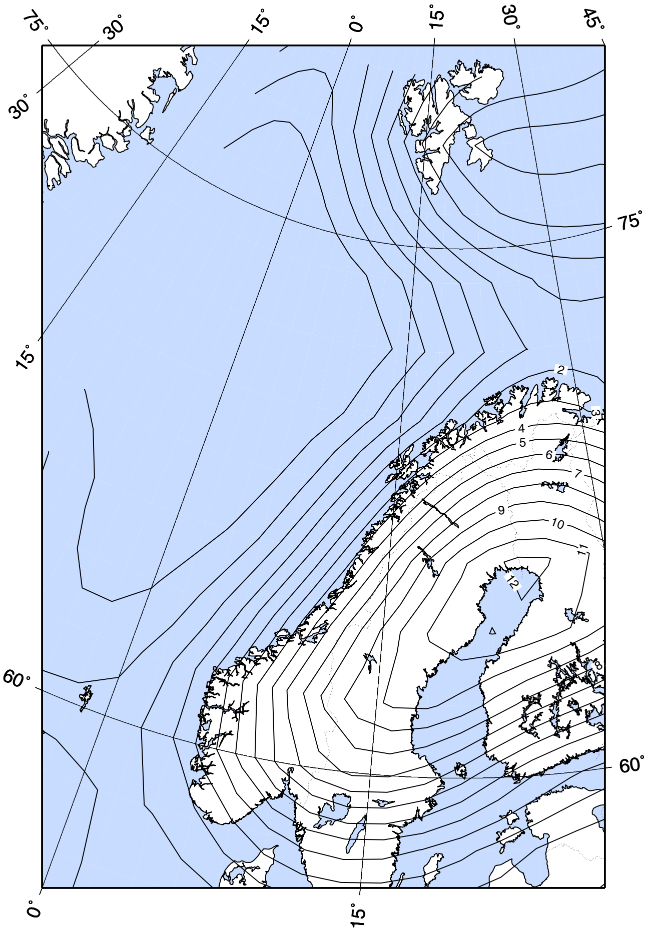

Figure 7: Vertical velocity predicted by the geophysical model.
The model is the one from (Milne et al., 1999). Separation of isolines is 1 mm/yr.

The other model is the geophysical model used above for predictions of horizontal velocities (Milne et al., 1999). Isolines of the vertical velocities for both models are shown in Figures 6 and 7.

In Figure 5, it is obvious that the vertical velocities determined from the 4-D points have much larger variance than the velocities from the permanent sites. For the permanent sites, agreement with the emphirical model (see Figure 6) is considerably better than with the geophysical model (see Figure 7). The geophysical model appears to overestimate the vertical velocities. This is particularly clear in Figure 8, where the two models are compared directly.

5 Conclusions

For Norway, a significant difference in horizontal motion predicted by NUVEL-1A-NNR and observed by GPS of the order of 3 mm/yr is found. Since ETRS is realised using the NUVEL-1A-NNR rotation pole for the Eurasian plate to account for the rigid tectonic motion, the Norwegian stations have a relative secular velocity with respect to EUREF89, the Norwegian realisation of ETRS, of the same order. Thus, the assumption of fixed coordiantes in EUREF89 leads to errors of the order of 3 cm/10 year if not corrected for the relative velocity.

The difference between NUVEL-1A-NNR predictions and observed velocities can only partly

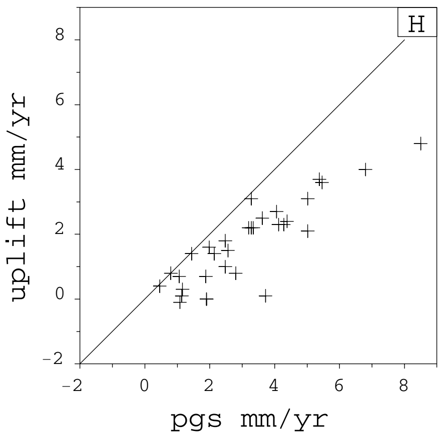

Figure 8: Comparison of the emphirical and geophysical land uplift models.
On the horizontal and vertical axis, velocities predicted by the geophysical model (Milne et al., 1999) and the emphirical model (Danielsen, 1999)) are given, respectively. The predicted values are given for all points where observed velocities are available. Symbols are the same as in Figure 2.

be explained by intraplate deformations due to post-glacial rebound. Using a new rotation pole for the Eurasian plate, as suggest by Altamimi & Boucher (2001) and recommended in Resolution 2 accepted by EUREF at the 2001 meeting, would on the one hand reduce the relative velocities with respect to a new realisation of ETRS89 for Norway to below 1 mm/yr. On the other hand, using this new rotation pole bears the danger that a large part of the horizontal intraplate motion due to postglacial rebound is absorbed in the ETRS89 realisation and affecting all other stations in Europe.

Therefore, we suggest that a more complex model equation is set up to represent both the rigid plate motion as well as major intraplate deformations. Using such an equation to separate between rigid plate motion and intraplate deformation would reduce the mutual bias of these effects. In particular, using a more complete equation for secular station motion including models of intraplate deformation together with the methodology used by Nocquet et al. (2001) to specify the stable part of a region, might help to identify regions of stability with less uncertainty.

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