Combination of GPS-observed vertical motion with absolute gravity changes constrain the tie between reference frame origin and Earth center of mass

H.-P. Plag*, C. Kreemer, W. Hammond
Nevada Bureau for Mines and Geology and Seismological Laboratory
University of Nevada, Reno, Mail Stop 1780, Reno, NV 89557, email: hpplag@unr.edu

Introduction
It has long been recognized that the Reference Frame Origin (RFO) of the International Terrestrial Reference Frame (ITRF) exhibits a secular trend with respect to the Center of Mass of the whole Earth system (CM). Even the most recent ITRF, namely ITRF2005 (Altamimi et al., 2002) and ITRF2008 (Altamimi et al., 2008) are expected to have a secular motion of the RFO with respect to CM of the order of 1 mm/year or more (e.g. Ray et al., 2004; Morehead & Williams, 2006). Such a secular trend would cause a global bias of vertical rates with a spherical harmonic degree of 2. This bias hampers the interpretation of vertical rates in terms of geodynamic processes. In particular, the apparent generally upward vertical motion of GPS sites in the Basin and Range Province with respect to ITRF2008 is contrary to the expectation based on a planet extending owing to gravitational collapse.

When geodetic observations are carried out (like the Global Positioning System (GPS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI)) the determining the relative positions between the receivers is possible when comparing the results to theoretical models. In order to determine the absolute position of a station, the relative position between the station and a known reference point is needed. In this paper, we will focus on the determination of the absolute position of the RFO.

The Data
We have collected published velocities of gravity for a globally distributed network of sites, for which also GPS observations were available. The spatial distribution of these stations is shown in Figure 1. All stations are found in North America and Europe.

All the GPS data were homogeneously processed with the GPS/IPASS-B (GIPSY) software package of Art Propulsion Laboratories (APL) using a Precise Point Positioning (PPP) method to determine daily coordinates. A full description of the analysis is given in Plag et al. (2002). All time series were determined in ITRF2000. The time series of daily station coordinates were then used to determine vertical rates taking into account secular and annual and annual harmonic components. The uncertainties of the vertical rates were estimated taking into account the general presence of colored noise in addition to white noise in these time series. The colored noise was approximated as flicker noise.

Theory
Following Wahr et al. (1999), the total gravity anomaly \( \delta g(\phi, \lambda) = \delta g(\phi, \lambda) - \delta g(\lambda) \) measured by a gravimeter \( \phi(\phi, \lambda) \) geometrically measured at time \( t \), can be written as

\[
\delta g(\phi, \lambda) = \delta g(\phi) + \delta g(\lambda) + \delta g(u(\phi)) + \delta g(v(\lambda)) + \delta g(g(\phi, \lambda)),
\]

where \( \delta g(\phi, \lambda) \) are the anomalies due to the vertical displacement \( \delta h(\phi, \lambda) \) of the instrument through the unperurbed gravity field and the actual mass effect caused by constant mass redistributions, respectively. It is the vertical position of the gravimeter. \( \delta g(\phi) \) is related to the vertical displacement by \( \delta g(\phi) = -2w \delta g/\delta \phi = 6 \delta \phi \delta \phi \). It is the Earth’s radius, \( 6.37109 km \) on average.

The mass contribution to the observed anomaly can be split up into an elastic part due to constant mass changes and the non-Euclidean attraction of the surface mass being redistributed and the incremental contribution caused by load-induced mass redistribution in the solid Earth and a viscous part resulting from past mass changes (only the viscous mass contribution in the solid Earth gives \( \delta g(\phi, \lambda) = \delta g(\phi) + \delta g(\lambda) \). Similarly, we can separate \( u = u_{\phi} + u_{\lambda} \) and \( v = v_{\phi} + v_{\lambda} \). PGR model studies show that

\[
\delta g(\phi, \lambda) = \delta u_{\phi} + \delta v_{\theta} + \delta u_{\theta},
\]

with \( \delta u_{\phi} \approx 0.05 \) mm/yr, \( \delta v_{\theta} \approx 1.1 \) mm/yr for ice sheet and mantle (e.g. Wahr et al., 1995; Fassb. & Hager, 2001; Plag, 2004). The fact that \( \delta g(\phi, \lambda) \) are relatively large, \( \delta g(\phi) \) and \( \delta g(\lambda) \) are small results in a large ratio of the two terms. Thus, gravity field measurements are strongly correlated to the RFO position and can be used to constrain the vertical rates.

Global Results
Since all points with reliable vertical rates are at relatively high latitude on the northern hemisphere, the stations determination does not allow to determine significant translations in the X and Y components. For a translation in the Z component, only the bias in a function of \( \cos(\phi) \). As a zero order approach, we considered the bias in constant mass redistribution of the gravity and vertical rates (Figure 2). For this regression, we have eliminated three stations with either large \( u \) or \( v \) (indicating present-day mass changes) or uncertain gravity or vertical rates. For the remaining 28 data points, the correlation coefficient between gravity and vertical rates is \( r = -0.92 < -0.65 \) with the lower and upper values being the 95% uncertainties. The unweighted regression line is \( v = -2.17 \pm 0.469 \times u + 1.226 \pm 0.618 \times u \) in years and \( x \) in mm/year.

Basin and Range
The extensive tectonics, contemporary near-surface tectonics and generally high gravitational potential energy (GPE) (Jones et al., 2000; Flach et al., 2000; Humphreys & Coblenz, 2007) of the Basin and Range Province suggest that gravity plays an active role in driving and/or guiding the modern Pacific North America plate boundary deformation. However, the degree to which such deformation is due to plate motion or plate/lithospheric forces is still in doubt.

Conclusions
The combination of absolute gravity and geometric sites provides a valuable constraint on the tie between RFO and CM. Despite a poor gravitational station distribution, published gravity trends combined with homogeneously determined vertical rates of translation of ITRF2000 with respect to CM along the Z axis of the order of 2 mm/year. This is comparable to the difference between ITRF2000 and ITRF2005, indicating that ITRF2005 is better constrained to the CM. Consequently, the reference frame of choice for studies of absolute gravity and vertical rates is ITRF2005.

Figure 2: Result of a regression of horizontal to vertical velocity rates.

Figure 3: Vertical rate differences for ITRF2005-ITRF2000 (left) and absolute gravity frame - ITRF2005 (right). Differences are in mm/year.

Figure 4: Vertical secular motion in the Western U.S.A Left: For the whole Western U.S. Right: Basin and Range Province. Rates are in mm/year and in the absolute gravity frame.