Effects of atmospheric pressure loading and seven-parameter transformations on estimates of geocenter motion and station heights from space geodetic observations

P. Tregoning
Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

T. van Dam
European Center for Geodynamics and Seismology, Luxembourg

Received 22 July 2004; revised 20 December 2004; accepted 3 January 2005; published 23 March 2005.

[1] Variations in fluid loads such as the oceans and the atmosphere deform the surface of the Earth. The accuracy of station coordinates, in particular, heights, that can be estimated depends on how well one can separate these surface deformations from the associated translational motion between the center of mass of the solid Earth and the total Earth (CM). We applied simulated atmospheric pressure loading effects to the coordinates of sites in the CM frame to explore to what level of accuracy both geocenter motion and accurate station coordinates can actually be recovered from geodetic analyses. We found that standard seven-parameter transformations (three rotations, three translations, scale) generally recover about 80% of the geocenter motion; however, the inclusion of a scale factor permits the aliasing of surface loading deformation, introducing scale errors of up to 0.3 ppb and daily height errors as large as 4 mm. This limits the geophysical studies that can be performed accurately using the results of geodetic analyses where the magnitudes of the signals are small (e.g., tectonic movement of tide gauges, uplift rates for interpreting glacial isostatic adjustment). The quality of the geodetic results is extremely sensitive to the number and distribution of sites used to estimate the transformations and becomes worse when regional (rather than global) sets of sites are used. If the scale factor parameter is omitted, then the amount of aliasing of surface loading effects is reduced considerably and more accurate site velocities and geocenter motion estimates are achieved.

Citation: Tregoning, P., and T. van Dam (2005), Effects of atmospheric pressure loading and seven-parameter transformations on estimates of geocenter motion and station heights from space geodetic observations, *J. Geophys. Res.*, *110*, B03408, doi:10.1029/2004JB003334.

1. Introduction

[2] The total mass of the Earth is composed of the solid Earth and the fluid loads at the surface such as the oceans and the atmosphere, snow loading and continental water storage. The center of mass of the solid Earth (CE) does not coincide with the center of mass of the total Earth (CM) (Figure 1); rather, the two are related by a translation (commonly called "geocenter motion") [e.g., *Farrell*, 1972; *Dong et al.*, 1997, 2003; *Blewitt*, 2003] and spatially and temporally varying deformation of the surface of the Earth.

[3] Unlike the CE reference frame, the CM frame is directly accessible by observation [*Blewitt*, 2003]. Space geodetic techniques such as satellite laser ranging (SLR) and Global Positioning System (GPS) involve observing Earth-orbiting satellites from tracking stations on the surface of the Earth. The satellites rotate around the center of mass of the total Earth (CM) and the coordinates of the tracking sites located on the surface of the Earth are defined in an International Terrestrial Reference Frame (ITRF). The realized nature of the ITRF is a CM frame in the long-term but is a center of figure frame (CF) in the short-term [*Dong et al.*, 2003] (Figure 1). Therefore space geodetic techniques are theoretically capable of providing estimates of the translation between CM and CF caused by the surficial mass distribution variations, although the parameterization of the satellite orbits could possibly accommodate some of this geocenter motion [*Watkins and Eanes*, 1997; *Blewitt*, 2003].

[4] The transformations between reference frames is an important part of any geodetic analysis, and the accuracy of the resulting estimates of geophysical parameters (e.g., site velocities and even the geocenter motion estimates themselves) are dependent upon how this process is undertaken.

0148-0227/05/2004JB003334$09.00

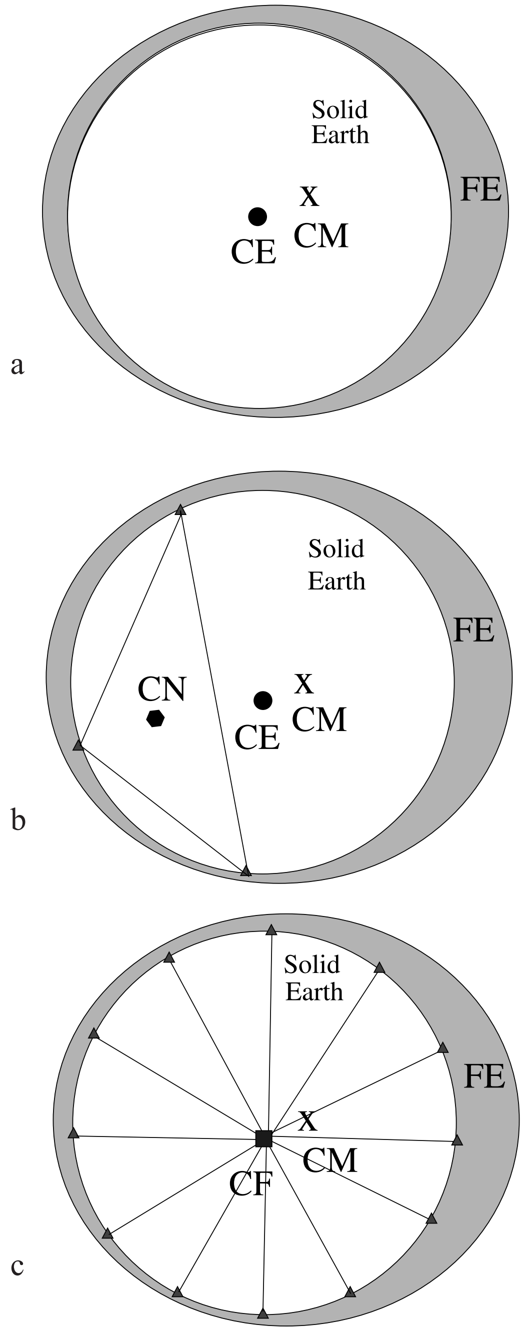

Figure 1. (a–c) Simplified illustration of the different reference frames used in geodesy. In Figure 1a, the solid circle represents the center of mass of the solid Earth (CE) while the cross represents the center of mass of the total Earth (CM), being the solid Earth plus the surface mass system in the fluid envelope (FE). In Figure 1b the center of network (CN, black hexagon) is different from both CE and CM in the extreme case of only three stations. In Figure 1c, in the theoretical situation of having geodetic sites evenly spaced over the entire surface of the Earth (including in the oceans), the center of figure (CF, solid square) approximates CE. Note that surface deformation associated with degree-1 surface loading has been omitted in order to simplify the figure.

Transformations not done correctly can yield coordinate/velocity errors that would lead to incorrect geophysical interpretations. To this end, we describe below how estimating a scale factor in transforming between reference frames actually degrades the accuracy of site coordinates and geocenter motion estimates when surface loads are present and unaccounted for.

[5] The relation between the CM and CF reference frames is straightforward: the coordinates of a site, i, in the frames can be written as

$$X_i^{\mathrm{CM}} + \epsilon_i^{\mathrm{CM}} = X_i^{\mathrm{CF}} + T + \epsilon_i^{\mathrm{CF}} \tag{1}$$

where T is simply a translation (in Cartesian coordinates) of the origin and represents the geocenter motion while ϵ_i^{CM} and ϵ_i^{CF} are the surface displacements of site i in the CM and CF frames, respectively, caused by the fluid loads. By construction, ϵ has a mean of zero when summed across the whole of the Earth because the translation, T, is the constant part of the deformation.

[6] A common approach to the analysis of space-geodetic observations is to first compute a "fiducial-free" network, that is, one in which the coordinates of the ground tracking stations are only loosely constrained [e.g., *Herring et al.*, 1991; *Heflin et al.*, 1992; *Zumberge et al.*, 1997]. The free network is then aligned with a terrestrial reference frame by computing a transformation of the site coordinates with respect to their externally derived values (e.g., their ITRF2000 values). In GPS analysis, a seven-parameter transformation is often estimated (three translations, three rotations, scale factor) [*Blewitt et al.*, 1992] where the translations are direct estimates of the geocenter motion between the CM and CF reference frames. Estimating geocenter motion in this manner (called the "network shift approach" by *Dong et al.* [2003]) has generally produced values with a large variation that appear to be quite sensitive to analysis procedures and are probably dominated by unmodeled noise sources [*Heflin et al.*, 2002; *Dong et al.*, 2003].

[7] *Wu et al.* [2003] transformed fiducial-free networks into the center of network (CN) frame (using seven-parameter transformations [*Heflin et al.*, 2002]), removed linear trends from the resulting time series and inverted the residuals for both the pattern of surface deformation and geocenter motion. The estimation of geocenter motion in this manner has been called the "degree-1 deformation approach" [*Dong et al.*, 2003]. Any errors introduced by the transformation process into the terrestrial reference frame will affect the accuracy of the geocenter motion estimates by this method. *Blewitt et al.* [2001] estimated simultaneously from GPS fiducial-free networks a time series of site coordinates, six-parameter transformations of weekly networks from the CM to the CF frame and global degree-1 Earth deformation. This process is not the same as the degree-1 deformation approach because the transformations between reference frames and the load moment are estimated at the same time rather than sequentially (D. Lavallée and G. Blewitt, personal. communication, 2004). The deformations predicted by their model have also been detected in very long baseline interferometry baselines [*Lavallée and Blewitt*, 2002].

[8] Here we scrutinize the process of transforming a set of coordinates from the CM to the CF frame. We used a one year simulated series of fiducial-free global polyhedra in the CM frame that include atmospheric pressure loading induced surface deformations and translations to assess to what extent these signals can be recovered and/or alias into other parameters in the transformation process. We also investigated the sensitivity of the process to the selection of sites used to estimate the transformations by using different sets of transformation sites. Our approach does not involve analyzing any actual space-geodetic observations but the conclusions are relevant to all techniques (e.g., SLR, GPS, DORIS) that involve transformations of networks from the CM to the CF frame.

[9] For clarity, we refer below to the sites used to compute the transformations as ‘‘transformation sites’’ and networks of such sites as ‘‘transformation networks.’’ A fiducial-free network may thus be composed of a transformation network (being the transformation sites used to transform from one reference frame to another) and the remaining sites that are not used in that particular transformation but that do get transformed into the other reference frame.

2. Surface Load

[10] In this study we look in detail at the effects of estimating geocenter motion by transforming loosely constrained coordinates, affected only by atmospheric pressure loading, into an ITRF using the network shift approach. The loading effects of other fluid loads can be expected to have similar effects (scaled by the difference in magnitudes of the loading) on the estimates of geodetic site coordinates and geocenter motion on daily time scales; therefore the conclusions from the results below can be extrapolated to other mass loading phenomena.

[11] The deformation of the surface of the Earth produced by changes in the mass of the atmosphere can be estimated from a knowledge of the atmospheric pressure at the surface by convolving Green’s functions to calculate the integrated deformation [e.g., *van Dam and Herring*, 1994; *Chen et al.*, 1999; *Moore and Wang*, 2003; *Petrov and Boy*, 2004]. We used global atmospheric pressure data from the NCEP Reanalysis and the details of the computation are described in detail by T. M. van Dam and P. Tregoning (Correcting GPS data for atmospheric pressure loading at the observation level, manuscript in preparation, 2005, hereinafter referred to as T. M. van Dam and P. Tregoning, manuscript in preparation, 2005). This is a simplified model that omits the diurnal and semidiurnal atmospheric tides; however, for the purposes of simulating a likely atmospheric pressure loading signal it suffices to capture only the first-order effect which is the daily to seasonal variations in atmospheric pressure. The omitted tidal effects have a maximum amplitudes of around 1 mm and 3 mm in the vertical component for the diurnal and semidiurnal tides, respectively [*van Dam et al.*, 2003].

[12] To compute the atmospheric pressure loading (ATML) displacements in the CM reference frame, we used a global convolution of the atmospheric pressure with Green’s functions which have been derived using degree-1 load Love numbers in the CM frame (all other load Love numbers to degree 144 remain the same in different reference frames) [*Farrell*, 1972; *Blewitt*, 2003]. Similarly, deformations in the CF frame were derived from Green’s functions using degree-1 load Love numbers in the CF frame.

[13] The same observations of atmospheric pressure were used to create the ATML in the CM and CF frames; therefore the computed loading effects, ϵ_i, at any site, i, in the CM and CF frames is can be expressed as

$$\epsilon_i^{\mathrm{CM}} = \epsilon_i^{\mathrm{CF}} + T_1 \quad (2)$$

where T_1 is the degree-1 translation of the geocenter from the CF origin to the CM origin. We refer below to these translations as the ‘‘true’’ degree-1 geocenter motion since they are known exactly from the numerical modeling of the ATML in the two reference frames.

[14] We generated a time series of these translations at 6 hourly intervals by calculating the difference in computed loading from the CF and the CM models. This value changes as a function of time, reflecting the changing nature of atmospheric pressure across the Earth. Previous studies have used such estimates of geocenter motion to derive spherical harmonic models for geocenter motion and to compare annual and semiannual variations with values derived from SLR analyses [e.g., *Chen et al.*, 1999]. What is of greater interest in this study are the small, daily variations and whether and how they alias into other parameters in the transformation from the CM to the CF reference frame.

[15] The atmospheric pressure loading includes higher-degree effects that average to a mean of zero across the entire Earth. However, discrete sampling of the loading effects may have the adverse effect of permitting the aliasing of higher-degree deformations into geocenter motion estimates when transforming from the CM to the CF reference frames.

[16] While we have used a simulated model for atmospheric pressure loading, it is based on actual global pressure variations and does represent realistic surficial deformations. A high correlation has been found on a site-by-site basis between predicted vertical motion and variations actually seen in GPS height time series (T. M. van Dam and P. Tregoning, manuscript in preparation, 2005).

3. Simulated Coordinates

[17] Imagine an analysis of a global network of space geodetic observations (e.g., SLR or GPS) that is perfect except for the modeling of atmospheric pressure loading. That is, the orbit force model matches precisely the motion of the satellites, the tropospheric and ionospheric delays are modeled exactly, solid earth tide, ocean tide loading models and all other physical phenomena are perfectly modeled but no consideration has been given to the effects of atmospheric pressure loading. A fiducial-free solution from such an analysis would produce a global polyhedron in the CM frame (because the artificial satellites rotate around the center of mass of the total Earth) where the ground tracking station coordinates would be the ‘‘perfect’’ estimates of the coordinates plus the station-dependent surficial loading effects (in the CM frame) caused by the unmodeled atmo-

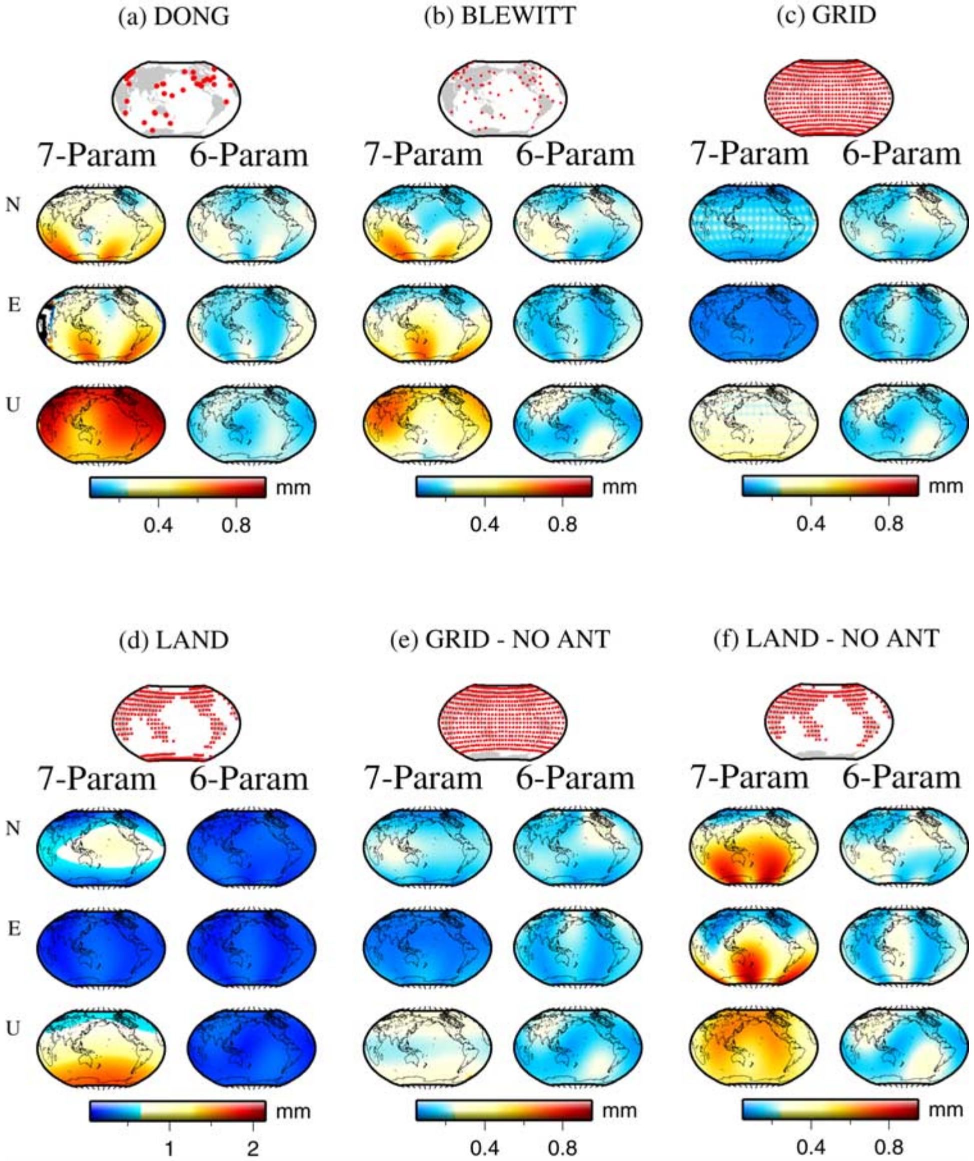

Figure 2. Transformation networks used to transform-free networks in the CM frame into the CF frame, and coordinate RMS after removing the ATML(cf). Results for six- and seven-parameter transformations are shown for each network: (a) 37-station network of *Dong et al.* [2002]; (b) 66-station network of *Blewitt et al.* [2001]; (c) 10° grid across the entire Earth; (d) only nodes in Figure 2c that lie over land; (e) as for Figure 2c but excluding nodes located on the Antarctic continent; (f) only nodes in Figure 2e that lie over land. Note that the scale range is different in Figure 2d from all the other plots.

spheric pressure loading. If the true coordinates of the sites were known, an analysis of such solutions could yield information about how ignoring the atmospheric pressure loading effects (origin translations and surface deformation) affects the accuracy of the final geodetic products of orbital parameters, geocenter motion and site coordinates.

[18] It is straightforward to simulate such a global polyhedron of station coordinates by adding the ATML (computed in the CM frame) for any number of sites to some a priori values of the sites in the CF frame. In so doing, one introduces the degree-1 translation of the origin from the CF to the CM frame as well as the site-specific surface deformations (which may include higher-degree effects as well). Using ATML values computed on different days permits a time series of global polyhedra to be created. Since this process requires no actual observations, one is free to generate site coordinates anywhere on the Earth including in ocean regions. Therefore we generated values for "realistic" sites where actual geodetic tracking stations exist but also on a regular 10° grid across the entire Earth.

[19] The result is a set of station coordinates for each day of 2001 that vary from day to day, where the variation is a result of only a translation between the origin of the CM and the CF frames as well as surficial deformation caused by atmospheric pressure loading. Both of these are quantities generated from the ATML model and are known exactly. For simplification, we set to zero the velocities of all sites so that the true estimate of the site coordinates is the same for every day. Any deviations from the a priori values therefore

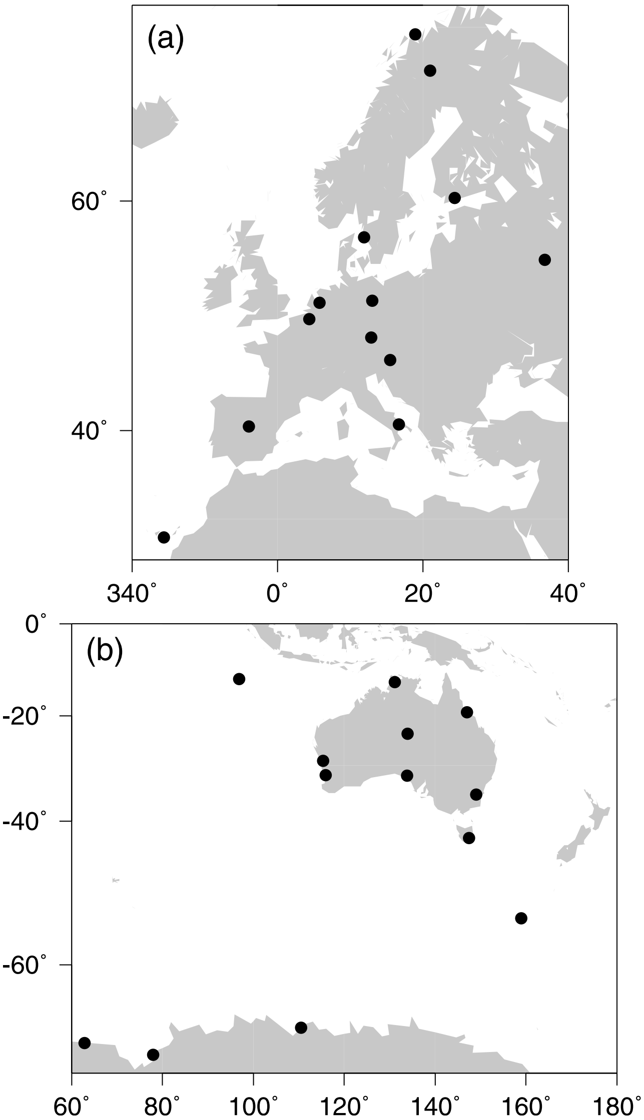

Figure 3. Regional transformation networks for (a) Europe and (b) CTA TIGA.

represent errors that have been introduced into station coordinates.

4. Results

[20] We transformed the daily polyhedra in the CM frame onto the a priori site coordinates in the CF frame and compared the estimates of the transformation parameters to the true values. In the case of the scale factor and the three rotation parameters, the true values are in fact zero. The translation estimates should be the translations between the CM and CF reference frames, with the values changing from day to day in a known way. The horizontal coordinates of all transformation sites were given equal weighting and we varied the ratio of weighting of heights with respect to horizontal coordinates as described below.

[21] We used several different selections of global and regional transformation sites (Figures 2 and 3) in order to assess whether this is important in the ability of the transformations to align the free network accurately in the CF frame. This actually has a major impact and the results for specific transformation networks are discussed in sections 4.2–4.4.

4.1. Rotations

[22] No rotations were introduced into the simulated site coordinates when adding the unmodeled ATML signal. No statistically significant rotations were estimated in the transformation of the coordinates from the CM to the CF frame. This indicates that unmodeled surface deformation signals in the coordinates do not alias into the rotation parameters of the transformation to the CF reference frame. This remained true irrespective of whether a six-parameter (no scale factor) or seven-parameter transformation was performed. The largest rotation estimated was 0.012 ± 0.014 μarc sec (uncertainty quoted is the formal 2σ uncertainty of the rotation estimate).

4.2. Translations

[23] The estimated translations should account exactly for the known geocenter motion between the CM and CF frames (assuming that no higher degree effects corrupt the translation parameters). We used two different transformation networks from previous GPS studies (37 sites from *Dong et al.* [2002], 66 sites from *Blewitt et al.* [2001]) with our simulated daily polyhedra and were not able to recover exactly the geocenter motion. The RMS coordinate error at each 10° grid point using these different transformation networks is shown in Figures 2a and 2b. The RMS of the differences for each Cartesian component of the translations are given in Table 1 and represent a likely "error" that results when transforming real geodetic networks from the CM to the CF reference frame. Less than 10–15% of the error may derive from the assumption that the CF frame is the same as the center of network frame, CN [*Wu et al.*, 2002]. We suggest that the sparsity and nonuniform distribution of the transformation sites has invalidated the assumption of equation (1) that the mean of the surficial deformations caused by the fluid loading must be zero at the transformation sites.

[24] To test this hypothesis, we computed the transformations using a transformation network composed of 612 sites spread across the Earth on a 10° grid (Figure 2c). This network samples the entire Earth, both the oceans and the land surfaces. The resulting geocenter translations are more accurate, but still not "perfect" with the RMS error reducing to 0.01 mm, 0.02 mm, and 0.29 mm for the X, Y, Z translations, respectively. The inclusion of sites on the Antarctic continent degrades the overall solution of the 10° grid transformation network; however, omitting sites south of 60° produces a solution that recovers more accurately the Z translation of the geocenter motion and the station heights (Figure 2e and Table 1).

[25] This was an unexpected result. The atmospheric pressure loading signal is very large and generally highly coherent across the whole of Antarctica. There is not the same landmass nor coherence across such a large continental region in the northern hemisphere polar region; therefore there is an asymmetry introduced because of the distribution of land on the surface of the Earth. There seems to be aliasing between the scale factor and Z translation param-

Table 1. RMS of Site Coordinates, Geocenter Errors, and Scale Factor Estimates Using Different Transformation Networks[a]

Transformation Network	Number of Sites[b]	Mean Site Coordinate Error RMS			RMS Geocenter Motion Error			RMS Scale Factor, ppb
		N, mm	E, mm	U, mm	X, mm	Y, mm	Z, mm	
Seven-Parameter Transformation								
Dong et al. [2002]	37	0.38	0.40	0.72	0.43	0.32	0.31	0.10
Blewitt et al. [2001]	66	0.32	0.36	0.46	0.28	0.40	0.21	0.06
10° grid	612	0.14	0.05	0.31	0.01	0.02	0.29	0.06
10°, land-only	300	0.54	0.21	1.08	0.14	0.22	0.76	0.15
10° (no Antarctic) grid	560	0.17	0.06	0.25	0.02	0.04	0.21	0.03
10° (no Antarctic), land-only	228	0.47	0.39	0.54	0.25	0.48	0.41	0.06
Six-Parameter Transformation								
Dong et al. [2002]	37	0.23	0.20	0.20	0.13	0.22	0.22	-
Blewitt et al. [2001]	66	0.22	0.17	0.22	0.11	0.20	0.23	-
10° grid	612	0.20	0.16	0.20	0.10	0.20	0.22	-
10°, land-only	300	0.24	0.20	0.23	0.12	0.25	0.25	-
10° (no Antarctic) grid	560	0.18	0.15	0.18	0.10	0.20	0.20	-
10° (no Antarctic), land-only	228	0.21	0.19	0.21	0.12	0.25	0.23	-
Europe	13				2.89	4.02	3.09	-
Australasian	12				1.06	1.33	0.80	-

[a]Site coordinates have been transformed from the CM to the CF frame and the atmospheric pressure loading (in the CF frame) has been subtracted subsequently.
[b]This is the number of sites used in the computation of the transformation, not the total number of sites in the network.

eters, both of which move site coordinates in roughly parallel directions close to the pole. A different sampling of the Earth (e.g., equal distance between grid nodes or even a higher density of nodes) would probably resolve this problem but we did not pursue this. Below we treat the grid solution without transformation sites in Antarctica as our "best" transformation network.

[26] We selected from this 10° grid (excluding the nodes located south of 60°S) the nodes that happen to fall on (or within a few hundred kilometers of) a landmass. This reduces the number of transformation sites from 612 to 300, still considerably more than used by *Blewitt et al.* [2001] (66 sites) or *Dong et al.* [2002] (37 sites) and in a more regular pattern than can be provided by existing geodetic tracking sites. The use of this transformation network (Figure 2f) produced geocenter motion errors similar to that of the 66 site network (Table 1) and is clearly inferior to the solution including fictitious sites over oceans.

4.3. Scale Factor

[27] Rather than simply averaging to a mean of zero across the Earth, the surficial deformations at the tracking sites get absorbed erroneously into the scale factor of the seven-parameter transformations. This has two adverse effects: it corrupts the geocenter translation estimates and introduces errors in the station coordinates, in particular, in the height component (see Figure 2). Since fluid loading occurs at all times, all geodetic analyses that have used seven-parameter transformations to align fiducial-free global polyhedra to a CF frame will have introduced errors into the coordinate estimates because of this aliasing.

[28] The pattern and magnitude of error in station coordinates depends upon the number and distribution of transformation sites. Figure 2 shows the RMS of coordinate errors (in north, east and up) over a 12 month period from seven-parameter transformations using different transformation networks. The pattern is very similar for the 37 and 66 station GPS transformation networks (Figures 2a and 2b), although the magnitude of the RMS error in height is reduced in the latter case, probably because the scale factor estimates from the 66 station transformations are generally smaller (Figure 4). Using a transformation network with a 10° spacing (excluding sites south of 60° on the Antarctic continent) yields a solution with an RMS of less than 0.3 mm in all components (Figure 2e). A solution using only grid nodes in Figure 2e that lie over continental landmass (but excluding the Antarctic sites) produces a pattern similar to the 66 transformation site solutions.

[29] In contrast, the results from six-parameter transformations (no scale factor estimated), using the same global polyhedra and transformation networks, have coordinate RMS values of ~0.2 mm (Table 1 and Figure 2). Here, there is no appreciable difference introduced by the changes in the transformation networks, indicating that the available distribution of space-geodetic tracking sites is capable of producing the correct answer. The remaining differences seen in the geocenter motion estimates are probably caused by higher-degree loading effects and by insufficient sampling of the Earth. We can place a current lower bound of ~0.2 mm (or ~1%) on the accuracy of geocenter motion estimates derived from the network shift approach if surface deformation caused by ATML is present.

4.4. Weighting of the Height Component

[30] The results of the seven-parameter transformations shown in Figure 2 have been computed with equal weights for north, east and height components. Decreasing the weight of the heights (e.g as suggested by *Dong et al.* [1998, 2002]) actually makes the results worse (Figure 5). Changing the weighting of the height component also increases the errors introduced in the six-parameter transformations. The downweighting of the heights permits unmodeled surface loading effects to be absorbed into the height parameters of the transformation sites, thereby destabilizing the transformation process and degrading the result.

[31] However, removing the heights altogether produces a similar result to that of weighting all components equally. Given that the height estimates from real obser-

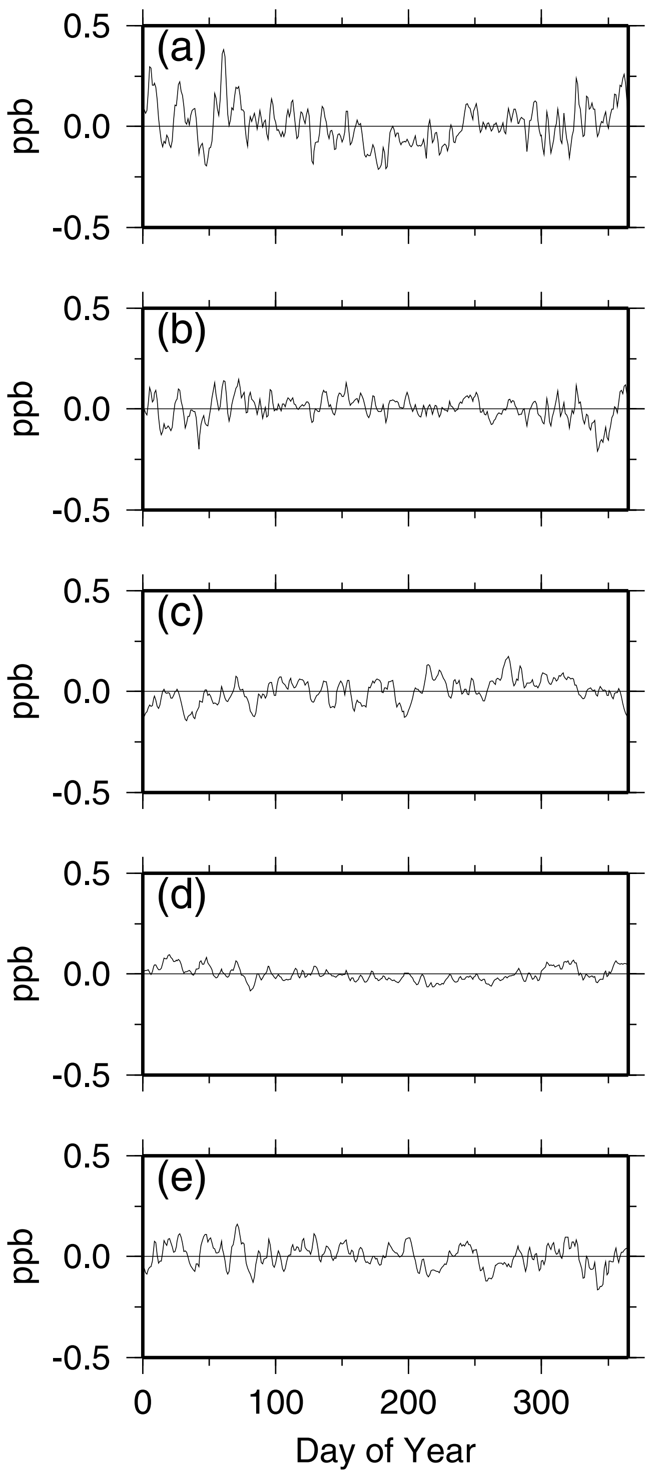

Figure 4. Daily scale factor estimates from different fiducial networks: (a) 37 sites of *Dong et al.* [2002]; (b) 66 sites of *Blewitt et al.* [2001]; (c) 612 sites on a 10° global grid; (d) as for Figure 4c but without Antarctic fiducial sites; (e) as for Figure 4d but only sites over land.

vations are likely to contain errors caused by mismodeling of tropospheric effects, antenna phase center variations etc, it makes sense to not use them at all in the transformation. The results of six-parameter transformations shown in Figure 2 were derived without including the height components.

5. Effect on Regional Networks

[32] Certain fluid loading signals correlate across large geographical regions. This can be seen by the spatially coherent (but temporally varying) deformation in the vertical component caused by atmospheric pressure loading (Figure 6). There is little chance that the loading deformation at a set of transformation sites in a regional network (albeit a network spanning thousands of kilometers) will average to a mean of zero. Consequently, the assumption of zero-mean surface deformation in equation (1) will be invalidated and the estimated geocenter translations will be incorrect.

[33] We computed six-parameter transformations using two regional transformation networks. The first spans western Europe (Figure 3a), while the other is the same as the regional network analyzed by the CTA TIGA-PP Analysis Centre [*Tregoning et al.*, 2004]. A large portion of the correlated surface deformation gets absorbed directly into the translation parameters, thus producing errors in the geocenter motion estimates (Figure 7 and Table 1). It has been recognized previously that geocenter motion estimates from regional networks are not reliable [*Davies and Blewitt*, 2000]; however, the effect of this on the resulting station heights has not been demonstrated.

[34] For the station at Maspalomas, located in the Canary Islands off the west coast of Africa, the RMS of the height time series using a global transformation network is 0.2 mm but 2.1 mm when the regional transformation network is used (both of these computations involve transforming into the CF frame then subtracting the modeled ATML signal. The RMS of the uncorrected height estimates is 2.3 and 0.6 mm for the regional and global solutions, respectively). The atmospheric pressure loading signal at the site is very small (Figure 7), with an RMS of 0.6 mm; however, the ATML effects at the other European sites have corrupted the transformations from the CM to the CF frame, thereby degrading considerably the accuracy of the height estimates at the coastal site of Maspalomas. The degradation is considerably worse than the small ATML signal present at the site.

[35] A similar situation arises using the much larger regional transformation network shown in Figure 3b, although the magnitude of degradation of the coordinate estimates is much smaller. The accuracy of the estimated geocenter motion is also greatly improved (Figure 7). In general, height estimates from a regional transformation network stabilization contain significantly more error than those derived from global transformation networks (Table 2).

6. Discussion

[36] *Blewitt et al.* [1992] converted the fudicial-free networks of *Heflin et al.* [1992] into the ITRF'90 reference frame using seven-parameter transformations. They stated that the scale of the systems are defined by the speed of light and gravitational coefficient, GM, and therefore that the scale factor parameter should be consistent with zero.

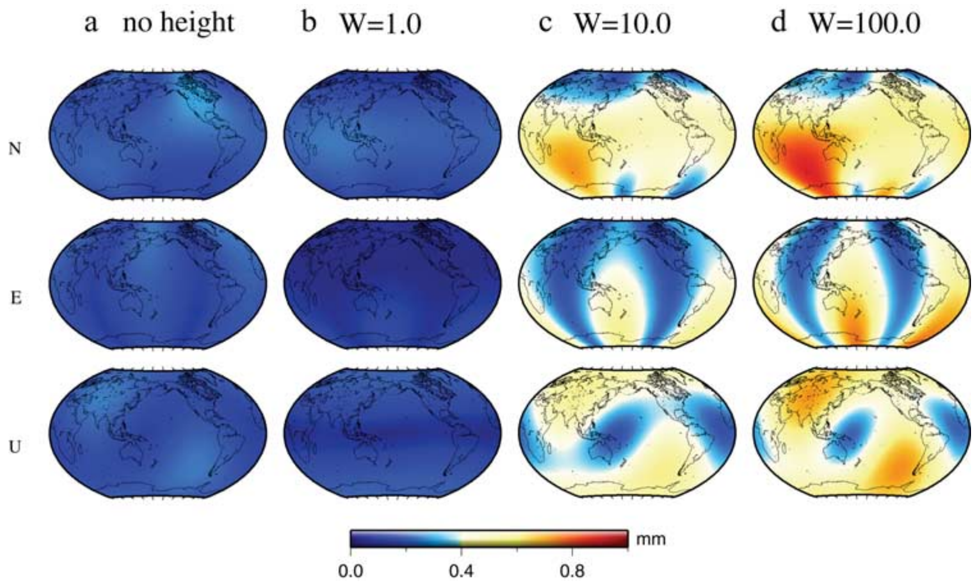

Figure 5. RMS coordinate errors (N, E, U) from six-parameter transformations with different weights applied to the contribution of station heights. (a) Height not used at all; (b) same as horizontal component; (c) height downweighted by a factor of 10; and (d) height downweighted by a factor of 100.

Transformations of free networks including scale factor parameters have been employed by *van Dam et al.* [1994], *Dixon et al.* [1997], *Zumberge et al.* [1997], *Mao et al.* [1999], *Freymueller et al.* [1999], *Davies and Blewitt* [2000], *Heflin et al.* [2002], *Willis and Heflin* [2004], and many other studies (the lists provided here and below are indicative rather than exhaustive).

[37] Studies using SLR either define the terrestrial reference frame by fixing site coordinates [e.g., *Bianco et al.*, 1998; *Schillak and Wnuk*, 2003] (hence do not estimate a transformation at all) or do not estimate a scale factor parameter [e.g., *Noomen et al.*, 1993; *Schwintzer et al.*, 1997; *Crétaux et al.*, 2002; *Moore and Wang*, 2003]. Other analysts have used only six-parameter transformations, for example, *Feigl et al.* [1993], *McClusky et al.* [2000], *Kreemer et al.* [2000], *van Dam et al.* [2001], and, although not explicitly stated, *Blewitt et al.* [2001], *Blewitt and Clarke* [2003], and *Gross et al.* [2004] (D. Lavallée and G. Blewitt, personal communication, 2004). Many other studies do not indicate how many parameters were estimated in the coordinate transformation process [e.g., *Crétaux et al.*, 1998; *Bouillé et al.*, 2000; *Larson and van Dam*, 2000; *Wahr et al.*, 2001; *Brondeel and Willems*, 2003]. *Dong et al.* [1998] examined the validity of estimating explicit translations and scale factor but left the question unresolved. We suggest that including a scale factor parameter in the transformation degrades the accuracy of the results if there are unmodeled surface deformations present in the free network polyhedra.

[38] *Heflin et al.* [2002] used daily seven-parameter transformations of fiducial-free GPS networks to estimate geocenter motion and variations in scale. Their time series of scale factor estimates for the most recent year of their analysis had a standard deviation of 0.3 ppb which they suggested may be caused by errors in mismodeling of tropospheric delay and antenna phase center patterns (both transmitter and ground reception antennae). The standard deviation of a single daily estimate of scale factor introduced into the seven-parameter transformations of our simulated coordinates is 0.1 ppb using the 37-station transformation network of *Dong et al.* [2002] and 0.06 ppb using the 66-station network of *Blewitt et al.* [2001] (Figure 4). These values are comparable to that of *Heflin et al.* [2002], and we suggest that unmodeled loading effects of atmospheric pressure loading may have contributed significantly to the variation in scale seen in their study.

[39] The most obvious way to prevent the site coordinates and geocenter translations from being corrupted by surface loading effects is to not estimate a scale factor when transforming from the CM to the CF frame. Is there a need to retain the estimation of a scale factor? The scale of the system is defined in the geodetic analyses of space geodetic observations by defining values for GM and the velocity of light; therefore there is no theoretical reason that a scale factor needs to be estimated when transforming from the CM to the CF reference frame unless a scale factor has been introduced somewhere by the mismodeling (or not modeling at all) of some real phenomena. Whether the definition of scale within the analysis of each technique is consistent between techniques is an independent issue beyond the scope of this study.

[40] An alternative approach is to correct for the surficial deformations before computing the transformations, either at the observation level or by applying daily averaged values to the coordinates of each site in the daily polyhedra. In this case, the total of all loading effects must be considered, including atmospheric pressure loading, ocean tide loading, ocean circulation variations, snow and water loading, changes in glaciers etc. It will not suffice to use a numerical model derived from a spherical harmonic series because the daily variations in some of the loading sources (e.g., atmospheric pressure loading) often exceed the maximum amplitude of such seasonal models (T. M. van Dam and P. Tregoning, manuscript in preparation, 2005) (see also Figure 7). If the loading deformations are modeled in the CM frame, then both the surface deformation and transla-

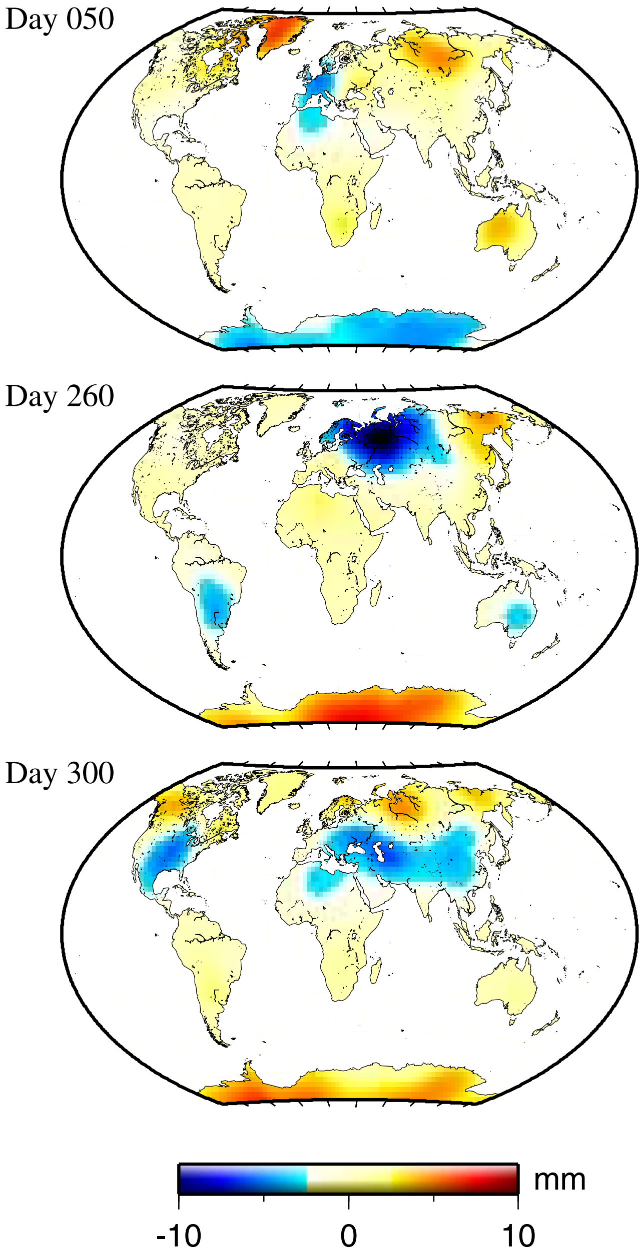

Figure 6. Deformation in the vertical component caused by atmospheric pressure loading on three different days during 2001.

tion of the origin will be removed (to within the accuracy of the models).

[41] Applying surface deformation corrections after the transformations have been computed for regional networks will not produce perfect results because it is likely that some of the deformation will have been absorbed by the translation parameters. This could reduce the apparent correlation of the height variations and the modeled deformations. Subsequently applying the loading deformation, in particular when regional transformation networks are used, can increase the variance of height estimates, in particular at coastal and island sites. Such increases have been attributed previously to errors in ocean tide loading models [*Brondeel and Willems*, 2003]. *Dong et al.* [2002] applied the corrections for atmospheric pressure loading prior to computing the transformations (D. Dong, personal communication, 2004) and will therefore not have degraded the accuracy of the coordinate estimates in their study.

[42] It is generally not stated in the literature in which reference frame loading deformations have been computed in studies of atmospheric pressure loading, ocean tide loading, etc. [e.g., *van Dam and Herring*, 1994; *van Dam et al.*, 1994; *Petrov and Boy*, 2004]. It is most likely that the calculations performed using the load Love numbers (or associated tabulated values) of *Farrell* [1972] have been computed in the CE reference frame. Our tests show that applying the loading in the wrong reference frame (i.e., correcting site coordinates in the CM frame with values computed in the CE frame) removes the surface deformations, leaving only the translation of the origin to be estimated in the transformation from the CM to the other frame. Including a scale factor parameter will not affect the accuracy of the transformation in this case, provided that the numerical models fully account for all loading effects. The omission of any of these effects (along with any errors in the numerical models) will affect seven-parameter transformations in the same manner as outlined in section 4.

7. Conclusions

[43] The transformation of fiducial-free geodetic networks computed in a CM reference frame into a surface-fixed CF frame can be problematic if deformation of the surface by fluid loads has occurred but has not been accounted for prior to the transformation. There will always be such deformation, since the mass of the atmosphere and oceans are being redistributed continuously. When a seven-parameter transformation is employed, only a fictitious network of transformation sites evenly spread across the whole of the Earth, including the oceans (but excluding Antarctica), is capable of separating the geocenter motion translations from the site-specific surficial deformations. All realistic geodetic transformation networks, and even a simulated 10° grid across all land surfaces, cause aliasing of the deformation into the translation parameters and, more significantly, into an erroneous estimate of a scale factor. This corrupts the resulting station coordinates and can introduce height errors on certain days of up to 4 mm in global analyses and up to 10 mm in regional analyses.

[44] When no scale factor is estimated the results of the six-parameter transformations are much more accurate. There remains an RMS of ~0.2 mm in all three site coordinate components but the process is able to recover correctly the geocenter translations between the CM and CF reference frames. This applies when the selected transformation network ranges from as few as 30 global stations through to a fictitious 10° evenly spaced grid. Weighting the height and horizontal components equally or excluding the heights altogether in the transformations produce similar results whereas downweighting the contribution of heights reduces the accuracy of the estimated site coordinates.

[45] Estimating a scale factor when transforming from the CM to the CF reference frame results in the parameter absorbing some of the real surficial deformations caused by loading phenomena. This has the unfortunate effect of degrading the subsequent station coordinates as well as

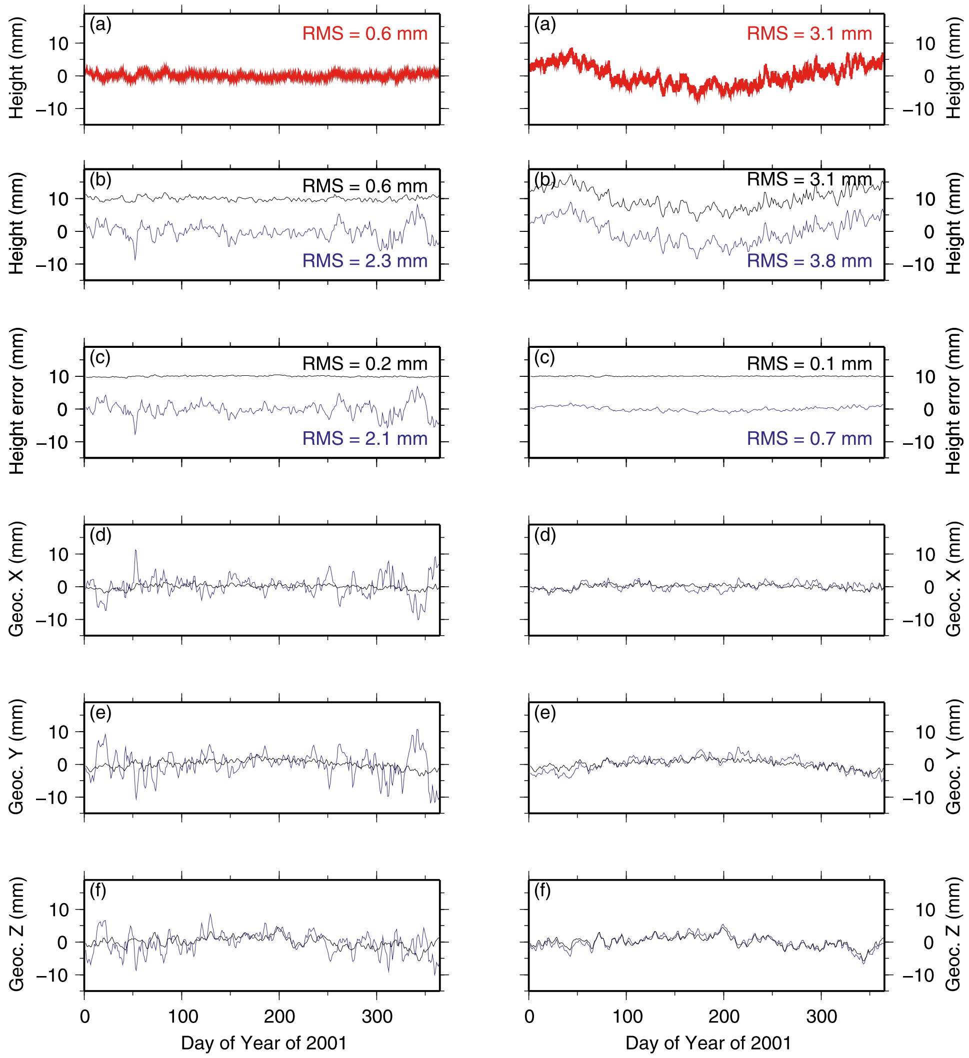

Figure 7. Errors introduced by atmospheric pressure loading effects at (left) Maspalomas in the Canary Islands and (right) Alice Springs in Australia when the six-parameter transformation from CM to CF is done with a regional transformation network. (a) Atmospheric pressure loading signal (red); (b) height estimates after the transformation to the CF frame from a regional (blue) and a global transformation network (black, offset by 10 mm); (c) height time series from regional (blue) and global (black, offset by 10 mm) stabilization when the true ATML signal in the CF frame is subsequently removed; (d–f) geocenter translation errors from regional (blue) and global (black) transformations: X (Figure 7d), Y (Figure 7e), Z (Figure 7f).

the estimates of geocenter motion. Even when geocenter motion is to be derived from the "degree-1 deformation approach" rather than the "network shift approach" the same conclusion applies. This process relies on the assumption that the coordinate residuals represent solely the degree-1 surface deformations and this will not be true if a seven-parameter transformation has been used because the station coordinates, in particular the heights, will have been corrupted by the erroneous scale factor estimates.

[46] In the case of regional networks, unmodeled surface deformations can introduce considerable errors into the transformation from the CM to the CF reference frame because the deformations are absorbed into the geocenter motion estimates. The smaller the regional network, the greater will be the error. Subsequently applying loading deformation corrections to site coordinates in the CF frame results in coordinates with an RMS error about 6 times

Table 2. Mean RMS Errors of Station Heights and RMS of Geocenter Errors From Transformations Using Global and Regional Networks

	Regional			Global[a]		
Site	N	E	U	N	E	U
			Europe Transformation Network			
KOSG	0.40	0.54	1.24	0.19	0.19	0.21
WTZR	0.40	0.52	1.34	0.19	0.18	0.23
MATE	0.47	0.51	1.13	0.21	0.18	0.22
			Australasian Transformation Network			
TIDB	0.19	0.14	0.49	0.24	0.21	0.13
PERT	0.23	0.21	0.61	0.30	0.16	0.12
DAV1	0.66	0.15	0.54	0.29	0.10	0.18

[a]The coordinate RMS listed here are from the solutions using the transformation network of *Blewitt et al.* [2001].

greater than that resulting from transformations using a global transformation network. However, if the "regional" transformation network is sufficiently large (such as the CTA TIGA-PP network spanning about 1/8th of the Earth) then the error introduced into station coordinates is comparable in horizontal coordinates to that of a global stabilization and only ~2.5 times greater for the vertical component. To achieve accuracies from regional analyses that are comparable to results from global analyses, surface deformations (such as atmospheric pressure loading, snow loading etc) must be modeled prior to transforming the networks into the CF reference frame.

[47] The conclusions reached in this study relate to transforming coordinates from one reference frame to another and are not specific to any individual space-geodetic technique such as SLR or GPS. There may or may not be differences in scale between techniques that may require scale factors to be estimated when combining techniques; however, this is a separate issue entirely from that presented here. There are many possible ways that scale errors could be introduced into GPS analysis (e.g., errors in phase center models for tracking stations and satellite transmitters, different techniques used to define the scale of the ITRF2000 reference coordinates). We acknowledge that it may seem logical to compensate for these effects by estimating a scale factor when transforming from the CM to the CF reference frame. However, it must be realized that, in doing so, one not only perhaps reduces scale effects but at the same time actually introduces scale errors if there are unmodeled surface loading effects present. In all cases when surface deformation effects caused by fluid load mass redistribution are present in fiducial-free networks in the CM frame, estimating a scale factor when transforming the network into the CF reference frame will degrade the accuracy of the transformation.

[48] **Acknowledgments.** We thank K. Lambeck and D. Dong for many fruitful discussions on loading, reference frames, and geocenter motion and D. Lavallée and H. McQueen for constructive comments on an earlier version of this manuscript. T. Herring, S. Owen, and an anonymous reviewer provided helpful review comments. This study was funded in part by Fonds Nationale de la Recherche de Luxembourg grant FNR/03/MA06/06.

References

Bianco, G., R. Devoti, M. Fermi, V. Luceri, P. Rutigliano, and C. Sciarretta (1998), A contribution in the estimation of tectonic motion in crucial areas: The CGS96 SLR solution, *Tectonophysics*, *294*, 225–236.

Blewitt, G. (2003), Self-consistency in reference frames, geocenter definition, and surface loading of the solid Earth, *J. Geophys. Res.*, *108*(B2), 2103, doi:10.1029/2002JB002082.

Blewitt, G., and P. Clarke (2003), Inversion of Earth's changing shape to weigh sea level in static equilibrium with surface mass redistribution, *J. Geophys. Res.*, *108*(B6), 2311, doi:10.1029/2002JB002290.

Blewitt, G., M. B. Heflin, F. H. Webb, U. J. Lindqwister, and R. P. Malla (1992), Global coordinates with centimeter accuracy in the international terrestrial reference frame using GPS, *Geophys. Res. Lett.*, *19*, 853–856.

Blewitt, G., D. Lavallée, P. Clarke, and K. Nurutdinov (2001), A new global mode of Earth deformation: Seasonal cycle detected, *Science*, *294*, 2342–2345.

Bouillé, F., A. Cazenave, J. M. Lemoine, and J. F. Crétaux (2000), Geocentre motion from the DORIS space system and laser data to the Lageos satellites: Comparison with surface loading data, *Geophys. J. Int.*, *143*, 71–82.

Brondeel, M., and T. Willems (2003), Atmospheric pressure loading in GPS height estimates, *Adv. Space Res.*, *31*, 1959–1964.

Chen, J. L., C. R. Wilson, R. J. Eanes, and R. S. Nerem (1999), Geophysical interpretation of observed geocenter variations, *J. Geophys. Res.*, *104*, 2683–2690.

Crétaux, J.-F., L. Soudarin, A. Cazenave, and F. Bouillé (1998), Present-day tectonic plate motions and crustal deformation from the DORIS space system, *J. Geophys. Res.*, *103*, 30,167–30,181.

Crétaux, J., L. Soudarin, F. J. M. Davidson, M. Gennero, M. Bergé-Nguyen, and A. Cazenave (2002), Seasonal and interannual geocenter motion from SLR and DORIS measurements: Comparison with surface loading data, *J. Geophys. Res.*, *107*(B12), 2374, doi:10.1029/2002JB001820.

Davies, P., and G. Blewitt (2000), Methodology for global geodetic time series estimation: A new tool for geodynamics, *J. Geophys. Res.*, *105*, 11,083–11,100.

Dixon, T. H., A. Mao, M. Bursik, M. Heflin, J. Langbein, R. Stein, and F. Webb (1997), Continuous monitoring of surface deformation at Long Valley Caldera, California, with GPS, *J. Geophys. Res.*, *102*, 12,017–12,034.

Dong, D., J. Dickey, Y. Chao, and M. Cheng (1997), Geocenter variations caused by atmosphere, ocean and surface ground water, *Geophys. Res. Lett.*, *25*, 1867–1870.

Dong, D., T. A. Herring, and R. W. King (1998), Estimating regional deformation from a combination of space and terrestrial geodetic data, *J. Geod.*, *72*, 200–214.

Dong, D., P. Fang, Y. Bock, M. K. Cheng, and S. Miyazaki (2002), Anatomy of apparent seasonal variations from GPS-derived site position time series, *J. Geophys. Res.*, *107*(B4), 2075, doi:10.1029/2001JB000573.

Dong, D., T. Yunck, and M. Heflin (2003), Origin of the International Terrestrial Reference Frame, *J. Geophys. Res.*, *108*(B4), 2200, doi:10.1029/2002JB002035.

Farrell, W. E. (1972), Deformation of the Earth by surface loads, *Rev. Geophys.*, *10*, 761–797.

Feigl, K. L., et al. (1993), Space geodetic measurements of crustal deformation in central and southern California, 1984–1992, *J. Geophys. Res.*, *98*, 21,677–21,712.

Freymueller, J. T., M. H. Murray, P. Segall, and D. Castillo (1999), Kinematics of the Pacific-North America plate boundary zone, northern California, *J. Geophys. Res.*, *104*, 7419–7441.

Gross, R. S., G. Blewitt, P. J. Clarke, and D. Lavallée (2004), Degree-2 harmonics of the Earth's mass load estimated from GPS and Earth rotation data, *Geophys. Res. Lett.*, *31*, L07601, doi:10.1029/2004GL019589.

Heflin, M. B., et al. (1992), Global geodesy using GPS without fiducial sites, *Geophys. Res. Lett.*, *19*, 131–134.

Heflin, M. B., D. Argus, D. Jefferson, F. Webb, and J. Zumberge (2002), Comparison of a GPS-defined global reference frame with ITRF2000, *GPS Solutions*, *6*, 71–75.

Herring, T. A., D. Dong, and R. W. King (1991), Sub-milliarcsecond determination of pole position using Global Positioning System data, *Geophys. Res. Lett.*, *18*, 1893–1896.

Kreemer, C., J. Haines, W. E. Holt, G. Blewitt, and D. Lavallée (2000), On the determination of a global strain rate model, *Earth Planet. Space*, *52*, 765–770.

Larson, K. M., and T. van Dam (2000), Measuring postglacial rebound with GPS and absolute gravity, *Geophys. Res. Lett.*, *27*, 3925–3928.

Lavallée, D., and G. Blewitt (2002), Degree-1 Earth deformation from very long baseline interferometry measurements, *Geophys. Res. Lett.*, *29*(20), 1967, doi:10.1029/2002GL015883.

Mao, A., C. Harrison, and T. Dixon (1999), Noise in GPS coordinate time series, *J. Geophys. Res.*, *104*, 2797–2816.

McClusky, S., et al. (2000), Global Position System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *J. Geophys. Res.*, *105*, 5695–5719.

Moore, P., and J. Wang (2003), Geocenter variation from laser tracking of Lageos1/2 and loading data, *Adv. Space Res.*, *31*, 1927–1933.

Noomen, R., B. A. C. Ambrosius, and K. F. Wakker (1993), Crustal motions in the Mediterranean Region determined from laser ranging to LAGEOS, in *Contributions of Space Geodesy to Geodynamics: Crustal Dynamics*, *Geodyn. Ser.*, vol. 23, edited by D. E. Smith and D. L. Turcotte, pp. 331–346, AGU, Washington, D. C.

Petrov, L., and J. Boy (2004), Study of the atmospheric pressure loading signal in very long baseline interferometry observations, *J. Geophys. Res.*, *109*, B03405, doi:10.1029/2003JB002500.

Schillak, S., and E. Wnuk (2003), The SLR stations coordinates determined from monthly arcs of LAGEOS-1 and LAGEOS-2 laser ranging in 1999–2001, *Adv. Space Res.*, *31*, 1935–1940.

Schwintzer, P., et al. (1997), Long-wavelength global gravity field models: GRIM4-S4, GRIM4-C4, *J. Geod.*, *71*, 189–208.

Tregoning, P., P. J. Morgan, and R. Coleman (2004), The effect of receiver firmware upgrades on GPS vertical time series, *Cah. Cent. Eur. Géodyn. Séismol.*, *23*, 37–46.

van Dam, T. M., and T. A. Herring (1994), Detection of atmospheric pressure loading using very long baseline interferometry measurements, *J. Geophys. Res.*, *99*, 4505–4517.

van Dam, T. M., G. Blewitt, and M. B. Heflin (1994), Atmospheric pressure loading effects on Global Positioning System coordinate determinations, *J. Geophys. Res.*, *99*, 23,939–23,950.
van Dam, T. M., J. Wahr, P. C. D. Milly, A. B. Shmakin, G. Blewitt, D. Lavallée, and K. Larson (2001), Crustal displacements due to continental water loading, *Geophys. Res. Lett.*, *28*, 651–654.
van Dam, T., H.-P. Plag, O. Francis, and P. Gegout (2003), GGFC Special Bureau for Loading: Current status and Plans, in *Proceedings of the IERS Workshop on Combination Research and Global Geophysical Fluids, Bavarian Academy of Sciences, Munich, Germany, 18–21 November 2002*, *IERS Tech. Note 30*, edited by B. Richter, W. Schwegmann, and W. R. Dick, pp. 180–198, Int. Earth Rotation Serv., Paris.
Wahr, J., T. van Dam, K. Larson, and O. Francis (2001), Geodetic measurements in Greenland and their implications, *J. Geophys. Res.*, *106*, 16,567–16,581.
Watkins, M. M., and R. J. Eanes (1997), Observations of tidally coherent diurnal and semidiurnal variations in the geocenter, *Geophys. Res. Lett.*, *24*, 2231–2234.
Willis, P., and M. B. Heflin (2004), External validation of the GRACE GGM01C gravity field using GPS and DORIS positioning results, *Geophys. Res. Lett.*, *31*, L13616, doi:10.1029/2004GL020038.
Wu, X., D. F. Argus, M. B. Heflin, E. R. Ivins, and F. H. Webb (2002), Site distribution and aliasing effects in the inversion for load coefficients and geocenter motion from GPS data, *Geophys. Res. Lett.*, *29*(24), 2210, doi:10.1029/2002GL016324.
Wu, X., M. B. Heflin, E. R. Ivins, D. F. Argus, and F. H. Webb (2003), Large-scale global surface mass variations inferred from GPS measurements of load-induced deformation, *Geophys. Res. Lett.*, *30*(14), 1742, doi:10.1029/2003GL017546.
Zumberge, J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb (1997), Precise point positioning for the efficient and robust analysis of GPS data from large networks, *J. Geophys. Res.*, *102*, 5005–5017.

P. Tregoning, Research School of Earth Sciences, Australian National University, Mills Road, Canberra, ACT 0200, Australia. (pault@rses.anu.edu.au)

T. van Dam, European Center for Geodynamics and Seismology, Rue Josy Welter, 19, Walferdange L-7256, Luxembourg. (tvd@ecgs.lu)