Geocenter motions from GPS: A unified observation model

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Received 15 April 2005; revised 22 December 2005; accepted 4 January 2006; published 6 May 2006.

[1] We test a unified observation model for estimating surface-loading-induced geocenter motion using GPS. In principle, this model is more complete than current methods, since both the translation and deformation of the network are modeled in a frame at the center of mass of the entire Earth system. Real and synthetic data for six different GPS analyses over the period 1997.25–2004.25 are used to (1) build a comprehensive appraisal of the errors and (2) compare this unified approach with the alternatives. The network shift approach is found to perform particularly poorly with GPS. Furthermore, erroneously estimating additional scale changes with this approach can suggest an apparently significant seasonal variation which is due to real loading. An alternative to the network shift approach involves modeling degree-1 and possibly higher-degree deformations of the solid Earth in a realization of the center of figure frame. This approach is shown to be more robust for unevenly distributed networks. We find that a unified approach gives the lowest formal error of geocenter motion, smaller differences from the true value when using synthetic data, the best agreement between five different GPS analyses, and the closest (submillimeter) agreement with the geocenter motion predicted from loading models and estimated using satellite laser ranging. For five different GPS analyses, best estimates of annual geocenter motion have a weighted root-mean-square agreement of 0.6, 0.6, and 0.8 mm in amplitude and 21°, 22°, and 22° in phase for x, y, and z, respectively.

Citation: Lavallée, D. A., T. van Dam, G. Blewitt, and P. J. Clarke (2006), Geocenter motions from GPS: A unified observation model, *J. Geophys. Res.*, *111*, B05405, doi:10.1029/2005JB003784.

1. Introduction

[2] The mass contained in the Earth's fluid envelope (oceans, atmosphere, and continental water) is constant at human timescales. However, its distribution over the surface of the Earth changes continually. Much of this geographic redistribution of surface mass happens periodically at 24 hour to annual periods and is related to the rotation of the Earth on its axis (e.g., thermally driven atmospheric tides) as well as motion of the Earth around the Sun (e.g., annual global water cycle). In the absence of external forces the center of mass of the entire solid Earth and load system (CM) is a fixed point in space; relative to this point a change in the location of the center of mass of the surface load must (by conservation of linear momentum) induce a change in the relative location of the center of mass of the solid Earth (CE). This "geocenter motion" causes a detectable translation of a geodetic network attached to the solid Earth, relative to the center of satellite orbits, which is CM [*Chen et al.*, 1999; *Watkins and Eanes*, 1993; *Watkins and Eanes*, 1997]. While geocenter motion is principally a product of mass balance relations, the geodetic network is located on the surface of the solid Earth which also deforms because of redistribution of the load. Thus the same process (redistribution of surface mass) is expressed in the geodetic network in two quite different ways: displacement of the Earth's center related to mass balance and subsequent deformation of the solid Earth due to the load. For a totally rigid Earth, there would be no deformation; in an elastic Earth the deformational movement at a point can reach up to 40% of the magnitude of the geocenter trajectory and must be taken into account [*Blewitt*, 2003]. A graphical representation of these concepts is given in Figure 1.

[3] Estimates of geocenter motion from space geodesy are important since they fundamentally relate to how we realize the terrestrial reference frame [*Blewitt*, 2003; *Dong et al.*, 2003]. Conventionally, the center of the International Terrestrial Reference Frame (ITRF) is defined to be at the center of mass of the entire Earth system, i.e., CM [*McCarthy and Petit*, 2004]. Estimates of geocenter motion can also help to constrain models involving global redistribution of mass [*Chen et al.*, 1999; *Cretaux et al.*, 2002; *Dong et al.*, 1997] and sea level [*Blewitt and Clarke*, 2003], since they are directly related to the degree-1 component of the surface mass load. This is particularly relevant because current estimates of the degree-1 surface mass load derived

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0148-0227/06/2005JB003784$09.00

from environmental models disagree. A number of authors estimate the annual and semiannual components of geocenter motion induced by different models of surface mass redistribution [*Bouillé et al.*, 2000; *Chen et al.*, 1999; *Cretaux et al.*, 2002; *Dong et al.*, 1997; *Moore and Wang*, 2003]. While the geocenter motions from different atmospheric mass models tend to agree for all components, significant differences (up to 50%) are observed in annual and semiannual geocenter motion from ocean bottom pressure and, more importantly, from continental water mass. The standard deviation about the mean of the modeled annual geocenter from 11 different model combinations [*Bouillé et al.*, 2000; *Chen et al.*, 1999; *Cretaux et al.*, 2002; *Dong et al.*, 1997; *Moore and Wang*, 2003] suggests the precision of the modeled annual geocenter variation is on the order of $\sim$1 mm in amplitude and $\sim 20^\circ$ in phase.

[4] The Gravity Recovery and Climate Experiment (GRACE) mission results [*Tapley et al.*, 2004] will provide significant new information on the surface mass variations over the Earth down to periods of 1 month. However, the GRACE products do not include degree 1 to which GRACE is insensitive. The determination of degree-1 coefficients of the Earth's surface mass load from observational data and the discrimination of modeled environmental data sets is therefore left to other geodetic techniques such as satellite laser ranging (SLR), Doppler orbitography and radiopositioning integrated by satellite (DORIS) and the Global Positioning System (GPS).

[5] It should be noted that no geodetic estimates of secular geocenter motion currently exist; tectonic deformation will produce a net translation of the center of surface figure (CF) relative to the center of mass (CM) which is generally first removed by estimating tectonic velocities at each site. Only if a plate rotation model is used can such an estimate be made and so far is considered systematic reference frame error rather than physical signal [*Argus et al.*, 1999], much further work is required to solve this important reference frame issue. In this work the estimation is considered for the more common use of the term "geocenter motion," that is, assuming tectonic deformation has been first removed. This work does not reflect the ability of a network shift or Helmert transformation approach to resolve the aforementioned reference frame issues associated with what might be called secular "geocenter motion" or even its ability to resolve secular differences between reference frames.

[6] There have been a number of different approaches to estimating geocenter motions from geodetic measurements [*Ray*, 1999] including (1) the so-called "network shift approach" [*Blewitt et al.*, 1992; *Dong et al.*, 2003; *Heflin and Watkins*, 1999], also called the "geometric approach" [*Cheng*, 1999; *Pavlis*, 1999], which directly models the translation between coordinate frames, (2) the "dynamic approach" [*Chen et al.*, 1999; *Pavlis*, 1999; *Vigue et al.*, 1992], which estimates degree-1 coefficients of the geopotential, and (3) the "degree-1 deformation" approach [*Blewitt et al.*, 2001; *Dong et al.*, 2003], which equates solid Earth deformation caused by the load to geocenter motion. The dynamic and network shift approach are equivalent (where constraints are minimal), and in this work we only consider the latter. We note that describing the "network shift approach" as "geometric" is misleading because this approach principally depends on satellite dynamics to locate the Earth center of mass and so is fundamentally a dynamic approach. Here we are consistent with the terminology of *Dong et al.* [2003]. *Lavallée and Blewitt* [2002] show that even the nonsatellite technique of very long baseline interferometry (VLBI) is sensitive to geocenter motions via the degree-1 deformation. However, to quote *Boucher and Sillard* [1999], commenting on the geocenter series submitted to the 1999 International Earth Rotation Service (IERS) analysis campaign to investigate motions of the geocenter, "It appears that, even if Space Geodesy geocenter estimates are sensitive to seasonal variations, the determinations are not yet accurate and reliable enough to adopt an empirical model that would represent a real signal." Disagreement between different geodetic analyses is still considerably larger than that between loading models. Much of this disagreement comes from differences between GPS analyses; estimates from SLR tracking of LAGEOS 1 and 2 [*Bouillé et al.*, 2000; *Chen et al.*, 1999; *Cretaux et al.*, 2002; *Moore and Wang*, 2003] are in much better agreement.

[7] The source of the disagreement between GPS analyses has been difficult to track down; *Dong et al.* [2002] and *Wu et al.* [2002] estimate the size of the error in the network shift approach due to an imperfect network, and *Wu et al.* [2002] estimate aliasing errors in the degree-1 deformation approach. A number of authors [*Blewitt*, 2003; *Dong et al.*, 2003; *Wu et al.*, 2002] state that the network shift approach is biased by deficiencies in GPS orbit modeling but a quantitative consideration of how all errors trades off against each other for different networks and approaches has not been completed. Although *Dong et al.* [2003] suggest the degree-1 deformation approach produces more stable geocenter estimates, *Wu et al.* [2002] suggest the ignored higher degrees produce a significant error. This uncertainty in how best to estimate geocenter motions from GPS makes it difficult to recommend procedures for defining the terrestrial reference frame [*Ray et al.*, 2004] or make robust inferences about degree-1 surface mass loading. *Dong et al.* [2003] even suggest that given the improved precision of modern geodetic techniques geocenter motions should be included in the definition of the ITRF as estimable parameters.

[8] Current methods to model geocenter motion consider either the translational or the deformation expression of change in the center of mass of the surface load; here we test a model that unifies these two aspects. In principle, this is a better way to model geocenter motions: It is complete, in that all the displacements associated with geocenter motion are modeled, and it is also conventional, such that displacements are modeled in the CM frame. We complete an appraisal of possible errors in the current geocenter motion estimation strategies applied to GPS and make a comparison of the unified approach with these alternatives.

2. Estimating Geocenter Motions From Space Geodesy

[9] For mathematical convenience we define "geocenter motion" in the context of this paper as the 3-D vector displacement $\Delta\mathbf{r}_{\text{CF-CM}}$ of the center of surface figure (CF) of the solid Earth's surface relative to the center of mass

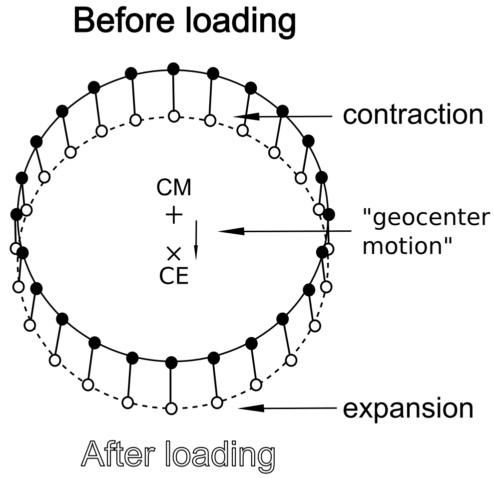

Figure 1. Graphical representation of displacements within a geodetic network due to changing location of center of mass of surface load. CM is center of mass of solid Earth plus load, the origin of satellite orbits which is essentially a kinematic fixed point in space. Two quite different expressions are observed: displacement of center of solid Earth (CE) and deformation of solid Earth.

(CM) of the entire Earth system (solid Earth, oceans, and atmosphere). Although the term "geocenter motions" has been used to describe the vector difference between a number of frames [*Blewitt*, 2003; *Dong et al.*, 1997], $\Delta\mathbf{r}_{CF\text{-}CM}$ or its opposite in sign ($\Delta\mathbf{r}_{CM\text{-}CF}$) are the most commonly estimated geocenter parameters from GPS [*Heflin et al.*, 2002; *Malla et al.*, 1993; *Ray*, 1999; *Vigue et al.*, 1992], SLR [*Bouillé et al.*, 2000; *Chen et al.*, 1999; *Cretaux et al.*, 2002; *Moore and Wang*, 2003], and DORIS [*Bouillé et al.*, 2000; *Cretaux et al.*, 2002], so we treat it as the desired estimable parameter. As discussed, the center of mass of the solid Earth (CE) is displaced from CM because of the changing location of the center of mass of the load. CF is a useful point that represents the geometrical center of the Earth's surface. It is displaced from CE because of the deformation of the solid Earth accompanying loading; if the Earth were rigid, these points would coincide. Since CF is essentially the global average of the surface deformation, it differs in location to CE by only ~2% [*Blewitt*, 2003]; however, this can be misleading since at specific locations the deformational displacement can be on the order of 40%.

[10] The three-dimensional displacement (east, north, and up) of a point on the Earth's surface due to surface mass loading can be described [*Diziewonski and Anderson*, 1981; *Farrell*, 1972; *Lambeck*, 1980] using spherical harmonic expansion and a spherically symmetric, layered, nonrotational and isotropic Earth model of the form

$$\begin{aligned} E(\Omega) &= \frac{\rho_S}{\rho_E}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\sum_{\Phi}^{\{C,S\}}\frac{3l'_n}{(2n+1)}T_{nm}^{\Phi}\frac{\partial_\lambda Y_{nm}^{\Phi}(\Omega)}{\cos\varphi} \\ N(\Omega) &= \frac{\rho_S}{\rho_E}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\sum_{\Phi}^{\{C,S\}}\frac{3l'_n}{(2n+1)}T_{nm}^{\Phi}\partial_\varphi Y_{nm}^{\Phi}(\Omega) \\ H(\Omega) &= \frac{\rho_S}{\rho_E}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\sum_{\Phi}^{\{C,S\}}\frac{3h'_n}{(2n+1)}T_{nm}^{\Phi}Y_{nm}^{\Phi}(\Omega) \end{aligned} \tag{1}$$

where T_{nm}^{Φ} are the spherical harmonic coefficients of the surface load density following the conventions of *Blewitt and Clarke* [2003] and expressed as the height of a column of seawater, h'_n and l'_n are the degree-n Love numbers which for degree 1 must be specified in our chosen frame [*Blewitt*, 2003], ρ_s is the density of seawater and ρ_E is the mean density of the Earth.

[11] It can be shown [*Trupin et al.*, 1992] that surface integration of (1) gives the following geocenter motion between the CM and CF frames:

$$\Delta\tilde{\mathbf{r}}_{\text{CF-CM}} = \left(\frac{\left([h'_1]_{\text{CE}} + 2[l'_1]_{\text{CE}}\right)}{3} - 1\right)\frac{\rho_s}{\rho_E}\begin{pmatrix} T_{11}^{C} \\ T_{11}^{S} \\ T_{10}^{C}\end{pmatrix} \tag{2}$$

We choose to use CE frame Love numbers in (2) since the $\frac{\left([h'_1]_{\text{CE}} + 2[l'_1]_{\text{CE}}\right)}{3} - 1$ term helps demonstrate the concept of translation and then deformation of the solid Earth. The unity term is the translation from CM to CE which is much larger than the first term which describes the average deformation of the solid Earth that displaces CF from CE. The first term has a magnitude of 0.021 using the Love numbers of *Farrell* [1972]; it is important to recall, however, that the deformation at a point given by (1) can be much larger than this.

2.1. A Unified Observation Model

[12] A unified approach for geocenter motion models displacements in the CM frame at each site using (1), where Love numbers are in the CM frame. In this way both the translation and deformation of the network are modeled. Strictly speaking, only the degree-1 deformation need be modeled as the higher degrees do not relate to the center of mass of the load. Higher-degree deformation will, however, be present in geodetic observations and could alias estimates of geocenter motion if not included, so it can be beneficial to include some of them. For short we call this unified model the "CM method." The design matrix for this approach is given in Appendix A.

[13] A note of caution must be attached to the CM method when anything but a full weight matrix is used during estimation. Estimating the translational aspects of geocenter motions relies on determining the CM frame via simultaneous solution for GPS satellite orbital dynamics and coordinates of a global site network. This information is present in the off diagonal elements of the stochastic model; information on the determination of individual site coordinates relative to the network as a whole is given along the diagonal. It is the stochastic model that determines the relative influence of translation and deformation on the estimate of geocenter motion. If the covariance matrix of observations is diagonal or block diagonal the translation of the network is effectively given a much larger weight than the deformation and the CM method gives identical results to the network shift method.

[14] This is particularly pertinent for GPS results obtained using precise point positioning [*Zumberge et al.*, 1997], in which orbits are fixed (considered perfect in the stochastic

model). While point positioning is a very useful approach for regional analysis, it is generally not suitable for estimating global parameters such as geocenter motion. The results obtained will be identical to those from the network shift approach for a global network and the same as common mode filtering [*Wdowinski et al.*, 1997] on a regional scale. *Davis et al.* [2004] attempt to estimate degree-1 deformation from continental-scale point-positioning results in this manner so that the remaining higher-degree (>1) deformation can be compared to GRACE measurements. However, *Davis et al.* [2004] have removed only a mean from their GPS results (and not the degree-1 deformation), so this is equivalent to common mode filtering on a continental scale.

2.2. The Network Shift Approach

[15] Estimation of $\Delta\mathbf{r}_{\text{CF-CM}}$ from GPS measurements has been most commonly performed by modeling displacements as a translation only [*Heflin et al.*, 2002; *Heflin and Watkins*, 1999]. Generally, a least squares approach is used to estimate a Helmert transformation with up to seven parameters [*Blewitt et al.*, 1992]. We follow [*Dong et al.*, 2003] in calling this the "network shift approach." This approach models only the translational aspect of geocenter motion, and it is easy to see how such a procedure could be developed from (2) since the globally averaged deformation is very small. Modeling coordinate displacements as only a translation, however, ignores the quite large deformations that can occur on a site by site basis and the estimate in reality defines a center of network (CN) frame [*Wu et al.*, 2002] giving geocenter motion $\Delta\mathbf{r}_{\text{CN-CM}}$ which is only an approximation of $\Delta\mathbf{r}_{\text{CF-CM}}$.

[16] When estimating a Helmert transformation it can be necessary to estimate rotation parameters since in fiducial-free GPS analysis network orientation is only loosely constrained [*Heflin et al.*, 1992]; however, a scale parameter should not be estimated. A scale parameter is sometimes included when estimating Helmert transformations to investigate any systematic differences in the definition of scale between different techniques, e.g., VLBI, SLR, GPS or DORIS [*Altamimi et al.*, 2002]. When estimating $\Delta\mathbf{r}_{\text{CF-CM}}$, however, there is no reason to include a scale parameter since we are using only one technique and the scale definition is the same. An estimated scale parameter could absorb some of the loading deformation due to an imperfect (e.g., continentally biased) network giving an apparent scale error; this error is unfortunate and can be completely avoided by not estimating scale.

2.3. Degree-1 Deformation Approach

[17] *Blewitt et al.* [2001] estimate the degree-1 coefficients of the surface mass load (expressed as the load mass moment) from GPS using a priori information about the Earth's elastic properties given by the loading model specified in (1) and the degree-1 Love numbers [*Farrell*, 1972] in the CF frame. By modeling only the deformation the translational aspect of geocenter motion does not influence the estimate. *Blewitt et al.* [2001] model GPS displacements in a realization of the CF frame with

$$[\Delta\mathbf{s}_i]_{\text{CF}} = \mathbf{G}^{\mathbf{T}} diag\left[[l_1']_{\text{CF}}[l_1']_{\text{CF}}[h_1']_{\text{CF}}\right]\mathbf{G}\frac{\mathbf{m}}{M_\oplus} \quad (3)$$

where $\mathbf{m}$ is the "load moment," $[h_1']_{\text{CF}}$ and $[l_1']_{\text{CF}}$ are degree-1 Love numbers in the CF frame, and for simplification the height and lateral degree-1 spherical harmonic functions (1) are identified with the elements of the geocentric to topocentric rotation matrix $\mathbf{G}$ (Appendix A). In the notation of this paper this is identical to (1) for the CF frame where we identify

$$\frac{\mathbf{m}}{M_\oplus} = \frac{\rho_s}{\rho_E}\begin{pmatrix} T_{11}^C \\ T_{11}^S \\ T_{10}^C \end{pmatrix} \quad (4)$$

and hence (3) is a method to estimate $\Delta\mathbf{r}_{\text{CF-CM}}$ through (2). [*Dong et al.*, 2003] named this the "degree-1 deformation" approach; this is an alternative method to the network shift but is dependent on the specific elastic Earth model (Love numbers) used in (3).

[18] *Blewitt et al.* [2001] did not provide details on how they realized the CF frame which led *Wu et al.* [2002] to incorrectly assume that the results of *Blewitt et al.* [2001] were biased by using Love numbers in the CF frame rather than the CN frame. In fact, *Blewitt et al.* [2001] used a stochastic approach [*Davies and Blewitt*, 2000] for implicit estimation of translation parameters, which can be shown [*Blewitt*, 1998] to be equivalent to explicit estimation using the functional model:

$$[\Delta\mathbf{s}_i]_{\text{OBS}} = \mathbf{t} + \mathbf{G}^{\mathbf{T}} diag\left[[l_1']_{\text{CF}}[l_1']_{\text{CF}}[h_1']_{\text{CF}}\right]\mathbf{G}\frac{\rho_s}{\rho_E}\begin{pmatrix} T_{11}^C \\ T_{11}^S \\ T_{10}^C \end{pmatrix} \quad (5)$$

In this approach the frame-dependent choice of degree-1 Love numbers used in (3) is inconsequential, because the translation parameter $\mathbf{t}$ ensures no-net translation of the network, thus the CN frame is realized. The design matrix for this deformation approach is given in Appendix A.

[19] This approach has the advantage that it is not subject to errors due to approximating $\Delta\mathbf{r}_{\text{CF-CM}}$ with $\Delta\mathbf{r}_{\text{CN-CM}}$ as in the network shift, and errors in the GPS determination of CM (orbit errors) which map equally (i.e., as a translation) into all site displacements are removed by the translation in (5). Removing common mode errors in site displacements by estimating a Helmert transformation and expressing displacements in a CN frame is common in GPS analysis [*Davies and Blewitt*, 2000; *Heflin et al.*, 2002; *Wdowinski et al.*, 1997]; however, the residual displacements had not been previously used to estimate degree-1 coefficients of the load. The results are still subject to errors due to the ignored higher degrees in (1) [*Wu et al.*, 2002] and GPS observational errors not common to all sites; both errors are of course network dependent.

[20] *Dong et al.* [2003], *Wu et al.* [2003], and *Gross et al.* [2004] extended this approach to estimate coefficients of the load up to degree 6 using equivalent forms of (1). Such an approach should reduce the errors in the estimate of degree 1 which may exist in the estimates of *Blewitt et al.* [2001] caused by ignoring the higher degrees [*Wu et al.*, 2002]. Additionally, estimating higher-degree terms requires a dense and well-distributed network.

[21] In their estimation procedure both *Dong et al.* [2003] and *Wu et al.* [2003] place their observations in the CN

frame by first removing a seven parameter Helmert transformation and estimating loading coefficients from the residuals. Both these results could be biased downward because of the inclusion (and subsequent removal from the displacements) of a scale parameter.

3. GPS Error Analysis

[22] In order to fully test the different techniques for estimating geocenter motion we first investigate the likely error sources involved. Errors are highly network dependent so it is crucial to considering different (but realistic) networks. The likely errors naturally fall into two categories: random and systematic GPS technique-specific errors and systematic errors due to mismodeling of the loading deformation. Random errors are considered in section 3.3 by propagation of the GPS formal error. The systematic effects of mismodeling are considered in section 4 by creating synthetic GPS data sets with known statistical properties so that the estimated value can be compared to the "true" value used to create the data. The effects of GPS-specific systematic errors are difficult to analyze here, orbit errors tend to affect the z component more than x or y since they are modulated by Earth rotation [*Watkins and Eanes*, 1994] and some degree of uncertainty in geocenter motion is attributable to not resolving ambiguities. Other GPS-specific systematic errors are also likely, such as second-order ionospheric effects [*Kedar et al.*, 2003] and tidal aliasing [*Penna and Stewart*, 2003]; however, their consideration is beyond the scope of this paper and we concentrate on the systematic errors, which are generated by the loading deformation itself, because of mismodeling.

3.1. GPS Data

[23] We use global GPS data from six International GNSS Service (IGS) analysis centers over the 7-year period 1997.25–2004.25: GeoForschungsZentrum (GFZ), the European Space Agency (ESA), the NASA Jet Propulsion Laboratory (JPL), Natural Resources Canada (EMR), the US National Geodetic Survey (NGS), and Scripps Institution of Oceanography (SIO). Weekly coordinate Solution Independent Exchange (SINEX) files [*Blewitt et al.*, 1995] from each analysis center are produced and archived each week as part of routine IGS activity. Each SINEX file contains a precise and rigorous estimate of the IGS polyhedron, using the most up-to-date methods and techniques [*Blewitt et al.*, 1995]; the orbit, timing and coordinate products from both the IGS and individual analysis centers are used in much of the ongoing global and regional scientific GPS processing, and the analysis center solutions are a core contribution to the ITRF.

[24] Each IGS analysis center processes its own particular subset of the IGS network, using software which can have quite different approaches to determining site coordinates from GPS data. As such they provide an ideal data set for exploring the errors in geocenter motions and the best method to estimate them, since the major processing software and strategies are represented yet produce solutions from the same GPS data. Most importantly, the SINEX format allows for complete archival of estimated site coordinates, the full variance-covariance matrix and the full set of applied constraints; these constraints can be subsequently removed to produce "loose" or "free" networks [*Davies and Blewitt*, 2000; *Heflin et al.*, 1992]. This is important since we wish to assess the determination of geocenter motions free from any particular frame that the individual analysis center has chosen to represent its weekly coordinates. Once these constraints are removed, the SINEX files form GPS realizations of the CM frame.

[25] Velocities are estimated and removed from the analysis center solutions using a consistent rigorous least squares strategy with full covariance information [*Davies and Blewitt*, 2000; *Lavallée*, 2000]. Sites with less than 104 weekly observations over 2.5 years are rejected. A period of 2.5 years is chosen to eliminate velocity errors associated with annual signals [*Blewitt and Lavallée*, 2002]. Outliers and data segments with known problems are rejected, and offsets due to equipment changes (particularly radome and antenna changes), earthquakes, or site moves are estimated. The analysis centers ESA and SIO do not apply the pole tide correction so this is applied using IERS standards [*McCarthy and Petit*, 2004].

[26] To maintain a consistent level of formal error scaling, the input weight matrices are scaled by the unit variance (chi-square per degree of freedom) in the case where residuals are estimated assuming the network shift approach, which is standard in GPS analysis. It is difficult to ascertain whether formal errors will be overestimated or underestimated in this case. If unmodeled observational errors are larger than the real geophysical loading then errors will be underestimated; conversely, if the loading dominates then this approach could overestimate the errors. We take this scaling to be at least a commonly accepted approach.

3.2. Networks

[27] The estimation of geocenter motions is fundamentally linked to the representation of the Earth's surface using a geodetic network. Network size and distribution are therefore key factors in the error assessment of different methods. The analysis centers have different approaches to choosing the weekly subset of the IGS global network they analyze. Figure 2 shows the number of sites analyzed each week after the rejections necessary to estimate the velocities mentioned in section 3.1. Some analysis centers such as EMR restrict their analysis to a small number of sites whereas SIO maintain an analysis that more closely mirrors the overall growth of the IGS network. A crude but informative way to assess network distribution, particularly in the context of geocenter motions, is to look at the percentage of sites within opposing hemispheres centered on the direction of each Cartesian axis. Figure 3 plots the percentage of sites in the hemisphere centered upon each coordinate axis, the center line at 50% represents an "ideal" equally distributed network. Although there are a number of factors, the distribution of a realistic global geodetic network is governed primarily by the ocean-land distribution (~70% of the Earth's surface is ocean). Figure 3 clearly reflects this: The inequality between the Northern and Southern Hemispheres in the z direction is the largest, reaching up to almost 80% of sites in the Northern Hemisphere, 30% larger than the "ideal." The inequality in the x and y directions varies up to only 15% yet there is still a noticeable tendency toward sites being located in the