

# Origin of the International Terrestrial Reference Frame

D. Dong, T. Yunck, and M. Heflin

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Received 17 June 2002; revised 14 January 2003; accepted 31 January 2003; published 16 April 2003.

[1] With recent improvements in space geodesy, the Earth's center of mass (CM) and center of figure (CF) are no longer indistinguishable. The current origin of the International Terrestrial Reference Frame (ITRF) is defined as the CM, which shows measured seasonal variations of several millimeters to 1 cm with respect to true CM. As scientists study Earth's dynamic deformations on seasonal and shorter timescales and begin to compare observed geocenter motion with predictions from geophysical models, the reference frame origin presents significant error due to missing the geocenter motion. This paper discusses the nature of the origin of the ITRF and explores the sensitivity of GPS measurements to geocenter motion. **We find that since the values of nonlinear geocenter motion are not included in the positions of the ITRF sites,** the behavior of the current ITRF origin reflects CM **on secular timescale** but reflects CF on seasonal and short timescales. The nature of the ITRF origin depends on both the adopted kinematic model and unmodeled network motion. The realized ITRF origin should be defined by a new nomenclature to reflect its nature accurately. By the new nomenclature, the origin will maintain its current long-term stability, while improving its stability on seasonal timescales to the submillimeter level. With the degree-1 deformation approach, GPS measurements are able to provide potentially valuable information on geocenter variations on seasonal and short timescales. *INDEX TERMS:* 1247 Geodesy and Gravity: Terrestrial reference systems; 1243 Geodesy and Gravity: Space geodetic surveys; 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1229 Geodesy and Gravity: Reference systems; *KEYWORDS:* origin, Terrestrial Reference Frame, GPS

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

## 1. Introduction

[2] The Terrestrial Reference System (TRS) is a fundamental basis for the geosciences [Boucher, 1990]. It provides a quantitative description of the position and motion of a target or an event on the Earth at any epoch, such as ground station, space satellite, missile, tornado or earthquake, and it is particularly critical in operational geodesy and navigation. The TRS is defined by its origin, scale, and orientation at a given epoch and its time evolution, and can be implemented by various types of systems [Boucher, 1990; McCarthy, 1996].

[3] The Conventional Terrestrial Reference System (CTRS) is a commonly adopted implementation of the TRS. As currently defined [McCarthy, 1996] the CTRS has these characteristics: (1) It is geocenter with its origin at the center of mass of the whole Earth, including oceans and atmosphere; (2) its scale is that of the local Earth frame within a relativistic theory of gravitation; (3) its orientation is initially given by the Bureau International de l'Heure (BIH) orientation at 1984.0; and (4) its time evolution in orientation will create no residual global rotation with respect to the crust. (There is a current proposal to refine

this to no rotational drift with respect to no-net rotation (NNR)-Nuvel-1A.) The CTRS monitored by the International Earth Rotation Service (IERS) is called the International Terrestrial Reference System (ITRS) and is considered an "ideal reference system" [Mueller, 1989, p. 155]. That is, its coordinates are fully defined, but not necessarily accessible. To make the CTRS available to the users, a set of accessible parameters must be constructed to materialize the system. **CTRS is realized by a set of station coordinates and velocities for a global network at a given epoch.** Together, these network coordinates and velocities constitute a reference frame. The realization of ITRS is called the International Terrestrial Reference Frame (ITRF). Since the ITRF is attached to the deformable Earth, to maintain the realization as close to the "ideal reference system" as possible, IERS publishes updated ITRF versions every few years, denoted as ITRF93, ITRF97, ITRF2000, etc. Owing to differences in selected IERS sites, observation data, and datum definitions, the various ITRF frames are not exactly the same. The coordinates in one ITRF must undergo a seven-parameter similarity transformation in order to be transferred to another ITRF. The transformation aligns the two ITRFs in a least squares sense; for individual sites, there are still differences.

[4] In recent years, the nature of the ITRF origin has attracted increasing attention for several reasons [Dong et

*al.*, 1997; *Argus et al.*, 1999; *Ray*, 1999; *Bouille et al.*, 2000; *Davis and Blewitt*, 2000; *Greff-Leffiz*, 2000; *Altamimi et al.*, 2001; *Blewitt et al.*, 2001; *Watkins et al.*, 2001; *Dong et al.*, 2002; *Altamimi et al.*, 2002]:

[5] 1. As more scientists study the dynamic deformation on seasonal and shorter timescales, the stability of the ITRF on those timescales becomes critical.

[6] 2. Many studies require comparison between space geodetic solutions and solutions from other geophysical data or models (atmosphere, oceans, etc). Consistency between the ITRF origin and the origins of other reference frames must be taken into account.

[7] 3. True geocenter (see definition in section 2) variations can be detected by space geodesy and can be quantitatively compared with geophysical model predictions.

[8] 4. The dual character of the ITRF origin (see sections 2–8) can easily cause confusion.

[9] In this paper, we examine the origins of various terrestrial reference frames. We then discuss the origin of the ITRF in particular and the determination of geocenter using space geodesy. Finally, we explore the sensitivity of Global Positioning System (GPS) measurements to geocenter motion.

## 2. Origins of Terrestrial Reference Frames

[10] There are three commonly adopted origins of terrestrial reference frames [*Dong et al.*, 1997; *Blewitt et al.*, 2001]: the center of mass of the whole Earth, including atmosphere, oceans and surface groundwater (CM), the center of mass of the solid Earth without mass load (CE), and the center of figure of the outer surface of the solid Earth (CF). The CM frame is commonly used in space geodesy because satellite dynamics are sensitive only to CM. The CE frame is used in certain theoretical geophysics studies (e.g., of the load Love number). The CF frame is often used in ground survey related disciplines, where the geometry between ground sites is the only measurable quantity. However, realizing and maintaining CM, CE, or CF frames in a deformable Earth is complicated.

[11] Assume a frame origin is AT (taking the first two characters of word “attached” as its name) and is attached to the surface of the deformable Earth. We use the superscript to represent the frame, the subscript to represent any point in the frame. In the AT frame, the CM, CE, CF positions are

Sum over whole Earth

$$X_{CM}^{AT}(t) = \frac{\sum X_i^{AT}(t)m_i}{\sum m_i}, \quad (1)$$

Sum over the solid Earth

$$X_{CE}^{AT}(t) = \frac{\sum X_i^{AT}(t)m_i}{\sum m_i}, \quad (2)$$

Sum over the solid Earth’s surface

$$X_{CF}^{AT}(t) = \frac{\sum X_i^{AT}(t)}{N}, \quad (3)$$

where  $N$  is the number of summation points,  $m_i$  is the mass at point  $i$ .

[12] The AT frame will become the CM, CE, or CF frame if  $X_{CM}^{AT}(t)$ ,  $X_{CE}^{AT}(t)$ , and  $X_{CF}^{AT}(t)$  are maintained to be zero, respectively. However, directly using equations (1) and (2) to realize CM and CE frames is very difficult, if not impossible. First, we must consider both position and mass, rather than position only. Second, we must consider both Earth’s surface and its interior, rather than surface only. For the CM, we must consider both the solid Earth and fluid layers, rather than solid Earth only.

[13] Using equation (3) to realize CF frame is also very difficult, if not impossible, because it requires the summation over the entire solid Earth’s surface including the newborn particles at the spreading centers and discarding the disappeared particles at the subduction zones.

[14] People often use the variations of the CF to define a CF frame, which are defined by

$$\delta X_{CF}^{AT}(t) = X_{CF}^{AT}(t) - X_{CF}^{AT}(t_0) = \frac{\sum [X_i^{AT}(t) - X_i^{AT}(t_0)]}{N}. \quad (4)$$

If the  $\delta X_{CF}^{AT}(t)$  is maintained to be zero, we can call this AT frame a CF frame. In this case, the origin of the frame can be any specified point, but the variation of the origin is the same as the CF.

[15] In practice, the origin of the AT frame is maintained by the constraint of no net residual translation. That is

$$\sum \delta X_i^{AT}(t) = \sum [X_i^{AT}(t) - X_{i,0}^{AT}(t)] = 0, \quad (5)$$

where  $X_{i,0}^{AT}(t)$  is the position in the AT frame based on a kinematic model, for example, the plate motion model from geological records or the site velocities determined from space geodesy. Thus the origin of the AT frame depends on the adopted kinematic model. If the kinematic model contains all motions viewed from a CM frame, the origin of the AT frame will be CM. Unfortunately, our current knowledge is far from reaching such a kinematic model. If the kinematic model represents the motions viewed from the center of Earth’s shape, the origin of the AT frame will be CF. Unfortunately, current kinematic models do not include all motions viewed from CF. Thus rigorously speaking, the current origin of the AT frame is neither CM nor CF.

[16] When we use a subset of stations to form the summation in equation (5), it defines the coordinate of the center of network (CN). The adopted kinematic model, which contains the motions from both plate motion and postglacial rebound, is critical to ensure that the CN is close to the frame origin of the kinematic model on the relevant timescale (for the current kinematic model, on a secular timescale). The ITRF origin is just such a CN, which depends on both the adopted kinematic model and the unmodeled network motion. In sections 3 and 4, we discuss impacts on the CN of the unmodeled network motion caused primarily by mass redistribution and the adopted kinematic model.

## 3. Mass Load Caused Geocenter Motion

[17] There are two established definitions for the commonly used term “geocenter”. One is the vector offset of CF relative to CM [*Vigue et al.*, 1992; *Dong et al.*, 1997;

Greff-Leffitz, 2000] and the other is the reverse: the vector offset of CM relative to CF [Trupin et al., 1992; Watkins and Eanes, 1997; Chen et al., 1999]. These are clearly the same but have opposite sign. Since the vector offset of CE relative to CF is due to degree-1 deformation and is much smaller than that of CM relative to CF (see next paragraph), some studies neglect the degree-1 deformation and their derived geocenter variations are actually CM relative to CE [Watkins and Eanes, 1997; Chen et al., 1999]. Here, we use CF relative to CM to define the geocenter.

[18] Both surface and internal mass redistribution can affect the geocenter. Here, however, since we are concerned primarily with seasonal geocenter variations, we specifically address the contribution from surface mass changes. Geocenter variations due to internal mass redistributions, for example, the Slichter modes of the inner core motion [Denis et al., 1997], are general negligible on such timescales.

[19] We use  $r^{\text{CM}}$ ,  $r^{\text{CE}}$ , and  $r^{\text{CF}}$  to represent the scalar or vector  $r$  defined under CM, CE, and CF frames respectively. The initial offsets between CM and CE, CM, and CF are  $f_{\text{CE}}$  and  $f_{\text{CF}}$ . When surface mass is redistributed, the CE will move within the CM frame through the mass balance relation [Dong et al., 1997]:

$$(M_e + M_{\text{load}})(X_{\text{CE}}^{\text{CM}} - f_{\text{CE}}) + M_{\text{load}}(X_{\text{load}}^{\text{CE}} + f_{\text{CE}}) = 0, \quad (6)$$

where  $M_e$ ,  $M_{\text{load}}$  denote mass of solid Earth and mass of surface load, respectively, and  $X_{\text{load}}^{\text{CE}}$  represents the position of the mass load center, so that  $M_{\text{load}}X_{\text{load}}^{\text{CE}}$  is equivalent to the degree-1 spherical harmonics of mass load distribution under a CE frame. For a deformable Earth, CF moves slightly further under a CM frame. Since  $M_{\text{load}} \ll M_e$  and  $f_{\text{CE}} \ll X_{\text{load}}^{\text{CE}}$ , we have [Trupin et al., 1992; Dong et al., 1997; Blewitt et al., 2001]

$$X_{\text{CE}}^{\text{CM}} = -\frac{M_{\text{load}}}{M_e + M_{\text{load}}}X_{\text{load}}^{\text{CE}} + f_{\text{CE}} \quad (7)$$

$$X_{\text{CF}}^{\text{CM}} = -\left(1 - \frac{h_1^{\text{CE}} + 2l_1^{\text{CE}}}{3}\right)\frac{M_{\text{load}}}{M_e + M_{\text{load}}}X_{\text{load}}^{\text{CE}} + f_{\text{CF}}, \quad (8)$$

where  $h_1^{\text{CE}}$  and  $l_1^{\text{CE}}$  are degree one mass load Love numbers defined under a CE frame,  $X_{\text{CF}}^{\text{CM}}$  is geocenter position.

[20] Thus CF further departs from CE by about 2% of the change of CE relative to CM [Trupin et al., 1992; Dong et al., 1997; Blewitt et al., 2001]. For a viscoelastic Earth, equation (8) is still valid but the mass load Love number  $h_1^{\text{CE}}$  and  $l_1^{\text{CE}}$  should use the corresponding Love number for a viscoelastic Earth, which includes an instantaneous elastic part and a viscous relaxation part [Greff-Leffitz, 2000].

[21] There is an alternative formula to calculate geocenter position [Bouille et al., 2000],

$$X^{\text{CM}} = -(1 + k_1)\frac{M_{\text{load}}}{M_e + M_{\text{load}}}X_{\text{load}}^{\text{CE}} + f, \quad (9)$$

where  $k_1$  is the degree one mass load Love number, and  $f$  is the initial offset between the reference origin and CM. The question arises: Is equation (9) consistent with equation (8)? The answer is “yes”. In solving the mass load Love

numbers, the degree one mass load Love number is reference frame-dependent. Because the three boundary conditions for solving  $k_1$ ,  $h_1$ , and  $l_1$  become dependent, adding an arbitrary rigid shift solution does not violate the boundary conditions [Farrell, 1972; Dahlen, 1976]. The constraint for solving the degree one mass load Love numbers is related to the choice of the origin of the reference frame. In a CM frame,  $k_1^{\text{CM}} = -1$ , so the degree one spherical harmonics caused by the surface mass load distribution and the solid Earth shift are mutually canceled. In a CE frame,  $k_1^{\text{CE}} = 0$ , so equation (9) gives  $X_{\text{CE}}^{\text{CM}}$ , i.e. equation (7). In a CF frame,  $k_1^{\text{CF}} = -(h_1^{\text{CE}} + 2l_1^{\text{CE}})$ , and equation (9) becomes (8).

[22] The observed position on the surface of the solid Earth under a CM frame is [McCarthy, 1996]

$$X^{\text{CM}}(t) = X_0^{\text{CM}} + V_0^{\text{CM}}(t - t_0) + \sum_i \Delta X_i^{\text{CM}}(t), \quad (10)$$

where  $X_0^{\text{CM}}$ ,  $V_0^{\text{CM}}$  are position and velocity at epoch  $t_0$ ,  $\Delta X_i^{\text{CM}}(t)$  are various nonlinear time-dependent deformations due to solid Earth tide, pole tide, ocean tide, mass loading from atmosphere, nontidal oceans, surface groundwater, postglacial rebound, coseismic and postseismic displacement, and other local effects. The observed position under a CM frame can also be represented as

$$X^{\text{CM}}(t) = X^{\text{CF}}(t) + X_{\text{CF}}^{\text{CM}}(t) \quad (11)$$

$$X^{\text{CF}}(t) = X_0^{\text{CF}} + V_0^{\text{CF}}(t - t_0) + \sum_i \Delta X_i^{\text{CF}}(t). \quad (12)$$

Here  $X^{\text{CF}}(t)$  is the observed position under a CF frame,  $X_0^{\text{CF}}$ ,  $V_0^{\text{CF}}$ , and  $\Delta X_i^{\text{CF}}(t)$  are defined under the CF frame. Comparing equation (10) with equations (11) and (12), it is straightforward to obtain

$$X_0^{\text{CM}} = X_0^{\text{CF}} + X_{\text{CF}}^{\text{CM}}(t_0), \quad (13)$$

$$V_0^{\text{CM}} = V_0^{\text{CF}} + V_{\text{CF}}^{\text{CM}}, \quad (14)$$

$$\sum \Delta X_i^{\text{CM}}(t) = \sum \Delta X_i^{\text{CF}}(t) + \Delta X_{\text{CF}}^{\text{CM}}(t), \quad (15)$$

where  $X_{\text{CF}}^{\text{CM}}(t_0)$  represents the geocenter position in the CM frame at the initial reference epoch;  $V_{\text{CF}}^{\text{CM}}$  represents the geocenter velocity in the CM frame, and  $\Delta X_{\text{CF}}^{\text{CM}}(t)$  represents the remaining nonlinear geocenter variations in CM frame.

[23] The current ITRF uses  $X_0^{\text{CM}}$ ,  $V_0^{\text{CM}}$  as the kinematic model. When the solutions are aligned to the ITRF frame by a seven-parameter similarity transformation, all common residual motions relative to the kinematic model are removed. The resultant solutions become

$$X(t) = X^{\text{CM}}(t) + \Delta X_{\text{CF}}^{\text{CM}}(t) = X^{\text{CF}}(t) + X_{\text{CF}}^{\text{CM}}(t_0) + V_{\text{CF}}^{\text{CM}}(t - t_0). \quad (16)$$

Since the CF frame is free to choose any point as its initial origin, it is customary to choose the CM at the initial reference epoch,  $X_{CF}^{CM}(t_0) = 0$ . Thus except for the secular motion, the behavior of the realized ITRF origin resembles CF on all other timescales.

#### 4. Impact of the Adopted Kinematic Model on the Realized ITRF Origin

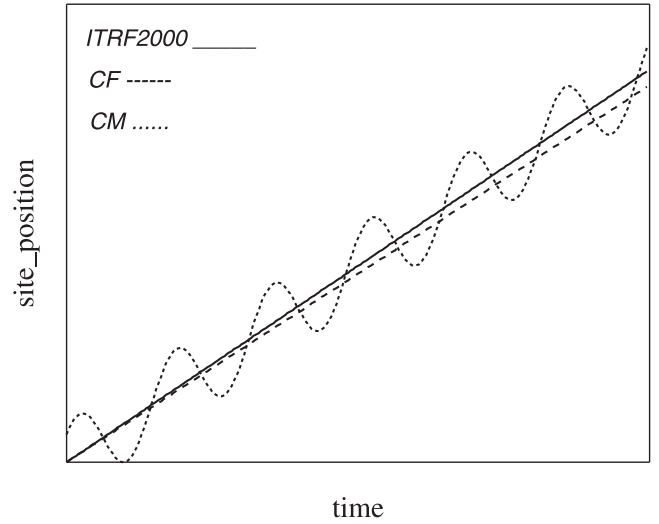
[24] Observed from the CM frame, every point at the Earth's surface undergoes two types of motion (for simplicity we neglect rotational motion, assuming that the rotational motion has been modeled perfectly). One is surface deformation motion due to plate tectonics, fault slip, postglacial rebound, tidal deformation, and various external and internal deformations caused by mass loading, such as magma intrusion, inner core translational motion, and mass redistribution in the atmosphere, oceans and groundwater. The other is the whole solid Earth surface shift due to mass balance of atmosphere, oceans, groundwater, and internal material of the solid Earth. Currently, most site deformations and solid Earth shift caused by mass loads are not modeled and removed. Only the secular site motions are modeled.

[25] From ITRF2000, the origin of the frame is defined by the weighted mean of the multiyear satellite laser ranging (SLR) solutions from five analysis centers [Altamimi et al., 2002]. Such an origin is maintained by the site velocities, which are derived from space geodesy with no-net translational motion relative to SLR solutions. Thus the adopted kinematic model consists of the site positions at the reference epoch and site velocities under a CM frame, given that the SLR technique is a good sensor of CM.

[26] Before ITRF2000, the kinematic models also consisted of site velocities, but were aligned to various plate motion models, for example, AM0-2 model [Minster and Jordan, 1978], NNR-NUVEL1 model [Argus and Gordon, 1991] and NNR-NUVEL-1A model [DeMets et al., 1994], through a seven-parameter transformation. Since these plate motion models predict that all sites move laterally with no radial motion at all, they are not complete kinematic models in a CF frame [Argus et al., 1999]. For the time being, we call it an incomplete kinematic model under a CF frame. The difference between a CF frame and an incomplete CF frame is mainly in  $z$  axis due to postglacial motion.

[27] It is unlikely that there is a significant secular drift between CF and CM based on geophysical considerations. On the decadal timescale (less than 100 years), however, the long-period surface deformation due to postglacial rebound, sea level and ice cover change can generate an apparent "secular" drift between CF and CM. At present, the geocenter secular drift estimated from observation data is still uncertain. The secular drift of the geocenter is derived as 0.2–0.5 mm/yr based on ICE-3G deglaciation model [Greff-Leffitz, 2000]. Also based on models, Argus et al. [1999] estimated the geocenter motions from postglacial rebound, sea level rise, continental drift, and mantle convection. All were <0.3 mm/yr.

[28] The current kinematic model only controls the secular behavior of the ITRF origin. For ITRF2000, the secular behavior of the frame origin resembles CM. Before ITRF2000, the secular behavior of the frame origin



**Figure 1.** Hypothetical site position time series in ITRF2000 (solid line), CF (dashed line), and CM (dotted line) frames.

resembled approximately CF due to the incomplete kinematic model under CF frame.

#### 5. Nature of the Realized ITRF Origin

[29] From the above discussion, we conclude that the desired nature of the ITRF2000 origin is CM. The adopted kinematic model is the site velocity field under a CM frame. The realized nature of the ITRF2000 origin becomes CM in the long term, but CF on seasonal and short timescales. Before ITRF2000, the desired nature of previous ITRF origins was also CM. The adopted kinematic model was the velocity field aligned to various plate motion models. The realized nature of previous ITRF origins was not CM but approximately CF on all timescales due to an incomplete kinematic model under a CF frame. The level of secular drift between CF and CM is about 0.5 mm/yr or less [Argus et al., 1999; Greff-Leffitz, 2000]. The level of geocenter variation at seasonal and short timescales is several mm to one cm [Dong et al., 1997; Watkins and Eanes, 1997; Chen et al., 1999; Argus et al., 1999; Bouille et al., 2000; Blewitt et al., 2001].

[30] Figure 1 shows a hypothetical site position time series in ITRF2000, CM and CF frames. For simplicity, we assume that all mass redistribution caused site deformations (but not common geocenter motion) are properly modeled. Thus the  $\Delta X_i^{CF}(t)$  terms in equations (13) and (15) disappear. We also assume that CF and CM coincide at the initial epoch,  $X_{CF}^{CM}(t_0) = 0$ . Thus this site shows purely linear motion under ITRF2000 frame. Under a CM frame,  $X^{CM}(t)$  have the same linear trend superimposed by seasonal and high frequency variations. Under a CF frame,  $X^{CF}(t)$  also move linearly but with a slightly different rate.

[31] In current data analysis, all mass load caused non-linear site motions  $\Delta X_i^{CF}(t)$  are not fully modeled. Note that the  $\Delta X_i^{CF}(t)$  terms cause different site-by-site motions, not a common motion. When the solutions are aligned to ITRF, only the common unmodeled variation at these aligned ITRF sites will cause the error of frame origin. If we select

30–40 globally distributed ITRF sites, the origin of such a frame will have seasonal instability at the submillimeter level [Dong *et al.*, 2002].

[32] We have shown the apparent conflict between the desired nature and the realized nature of the ITRF origin. This dual character (desired nature versus realized nature) of the ITRF origin did not present a problem a decade ago, when CM and CF were indistinguishable by geodetic measurements. Today, however, CM and CF are distinguishable. The nature and the stability of the realized ITRF origin should be further investigated.

## 6. Reconcile the Conflict Between Desired and Realized Natures of the ITRF Origin

[33] Historically, improvements in geodetic techniques have prompted the redefinition of the ITRF to meet new demands of scientific research. For example, when geodesy was able to measure tectonic motion directly, the ITRF introduced secular motion to its site positions. More than a decade ago, scientists recognized the weakness of the defined frame origin [Mueller, 1989, p. 169]: “A time-dependent error in the position of the center of mass, considered as the origin of a terrestrial frame, may introduce spurious apparent shifts in the position of stations that may then be interpreted as erroneous plate motions. To avoid this problem the parameters defining the CTS frame (i.e. the CTRS frame in this paper) should include translational terms as well.” Now, space geodesy is able to measure complex nonlinear geocenter motion, and scientists aggressively study Earth deformation on seasonal and short timescales. It is therefore time to reexamine the definition of the ITRF origin.

[34] The conflict between desired nature and realized nature of the ITRF origin stems from the unmodeled geocenter motion. How to treat the geocenter motion becomes a key to reference frame definition. We consider the following two possible choices:

[35] 1. Retain the definition of the ITRF origin as CM and call the missing seasonal and short-period geocenter motions the reference frame “error”. When the nonlinear geocenter motion can be modeled reliably, add the modeled nonlinear geocenter motion to the kinematic model.

[36] 2. Treat the unmodeled geocenter variations as estimated parameters. Define the kinematic model-dependent nature of the ITRF origin explicitly and accurately. The nomenclature for the ITRF origin will be that from a consensus. In this paper, we tentatively call it CN to distinguish it from either CM or CF. The transformation between CN, CM and CF frames is explicitly defined by equation (16). The transformation between CM and CF frames is defined by equation (11).

[37] We prefer the second choice. First, the “error” of reference frame origin is greatly reduced because the new nomenclature describes the ITRF origin accurately. In seasonal timescales, the origin instability is reduced from the several millimeters to 1 cm level to the submillimeter level. For secular motion, it preserves the same stability as the current ITRF origin definition.

[38] Second, in the absence of a good predictable model we can still remove geocenter variations by estimation of daily offsets. The estimated geocenter time series may be

used to construct a model, which could then be used in choice 1. Removing geocenter variations from the position time series simplifies plate motion, postglacial rebound and mass load caused deformation studies. Since we are a long way from a reliable geocenter motion model, it is more natural to treat geocenter motion as external parameters rather than having them wrapped into the time-dependent site positions.

[39] Third, the nature of the solution aligned to the ITRF frame is much clearer. For example, if we compare the solutions aligned to ITRF2000 with those from plate motion model predictions or finite element simulations, there is an explicit error due to the missing transformation from ITRF2000 to the CF frame. This error is 0.5 mm/yr or less for secular motion and at the submillimeter level on seasonal timescales. Using the definition of the ITRF2000 origin from the first choice, however, such a comparison has double implicit errors. One is the ITRF origin error due to missing seasonal and short-period geocenter motions. One is the missing transformation from ITRF (assume to be CM frame) to the CF frame. Both errors are several millimeters to 1 cm on seasonal timescales, and actually are mostly canceled out. The second error also has secular motion error at 0.5 mm/yr or less level.

[40] Under the second choice, the transformation between the celestial reference frame (CRS) and the CN frame involves two steps [McCarthy, 1996]:

$$X^{\text{CRS}}(t) = PN(t)R(t)W(t)X^{\text{CM}}(t) \quad (17)$$

$$X^{\text{CM}}(t) = X_{\text{CN}}^{\text{CM}}(t) + D(t)X^{\text{CN}}(t), \quad (18)$$

where  $X^{\text{CRS}}(t)$ ,  $X^{\text{CM}}(t)$ ,  $X^{\text{CN}}(t)$  are geocenter coordinates in CRS, TRS (CM origin), TRS (CN origin) frames respectively.  $P$ ,  $N(t)$ ,  $R(t)$ ,  $W(t)$  are precession, nutation, spin, and polar motion matrices respectively (see definitions of McCarthy [1996]);  $X_{\text{CN}}^{\text{CM}}(t)$  is network center motion, and the degree-1 deformation in the CN frame is included in  $X^{\text{CN}}(t)$ ; and  $D(t)$  is the transformation matrix which absorbs the unmodeled frame rotation and scale difference. In GPS data analysis, the free network solution  $X^{\text{CM}}(t)$  is aligned to an ITRF through a seven-parameter transformation, which estimates the  $X_{\text{CN}}^{\text{CM}}(t)$  and  $D(t)$  and shifts the origin of the reference frame from CM to CN (defined by aligned ITRF sites) and rotates the frame orientation to the ITRF orientation.

[41] Of course, the final choice involves more considerations than these. There may be other choices. We leave the question for further discussion.

## 7. Determination of Seasonal Geocenter Motion by Space Geodesy

[42] The biggest unmodeled component of the current kinematic model is the seasonal degree-1 deformation in the CM frame, which is composed of the motion of CF relative to CM plus the degree-1 deformation in the CF frame. Determination of the seasonal geocenter motion is critical for the improvement of the ITRF origin. It is commonly accepted that satellite laser ranging (SLR) is currently the

**Table 1.** Measured and Predicted Annual Variations of Geocenter Motion<sup>a</sup>

	<i>x</i>		<i>y</i>		<i>z</i>	
	Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg
Lageos 1 and 2 <sup>b</sup>	2.2	211	3.2	331	2.8	225
Lageos 1 and 2 <sup>c</sup>	2.1 ± 0.5	223	2.0 ± 0.5	308	3.5 ± 1.5	228
Doris (T/P) <sup>d</sup>	1.8	205	5.0	349	3.0	298
GPS <sup>e</sup>	3.3 ± 0.3	184 ± 3	4.8 ± 0.3	285 ± 3	11.0 ± 0.2	214 ± 1
<i>Dong et al.</i> [1997] <sup>f</sup>	4.2	224	3.2	339	3.5	235
<i>Chen et al.</i> [1999]	2.4	244	2.0	270	4.1	228
<i>Bouille et al.</i> [2000]	1.6	236	1.8	309	3.1	254

<sup>a</sup>Values after symbol ± represent formal uncertainties. Amplitude  $A$  and phase  $\phi$  are defined by  $A \sin[\omega^*(t - t_0) + \phi]$ , where  $t_0$  is 1 January and  $\omega$  is the annual angular frequency.

<sup>b</sup>Solutions from *Eanes et al.* [1997].

<sup>c</sup>Solutions from *Bouille et al.* [2000].

<sup>d</sup>Solutions from *Bouille et al.* [2000].

<sup>e</sup>Solutions from *Blewitt et al.* [2001]. The results are transformed from degree one mass load to geocenter based on equation (8).

<sup>f</sup>Sign error of geocenter  $z$  component caused by groundwater [*Dong et al.*, 1997] has been corrected here.

best space geodetic technique to measure the geocenter [*Watkins and Eanes*, 1993; *Altamimi et al.*, 2001, 2002]. Very long baseline interferometry (VLBI) is not directly sensitive to the TRF origin owing to the parallel ray paths from remote quasars. However, VLBI can sense the geocenter motion indirectly through degree-1 deformation [*Lavalley and Blewitt*, 2002]. GPS and DORIS can sense the TRF origin through satellite dynamics, and more recently through low Earth orbiting (LEO) GPS receivers, though no firm LEO results are yet in.

[43] Table 1 lists the annual geocenter motion derived from SLR, GPS, and DORIS data and from predictions of surface mass redistribution. The amplitude  $A$  and phase  $\phi$  are defined by  $A \sin[\omega^*(t - t_0) + \phi]$ , where  $t_0$  is 1 January and  $\omega$  is the annual angular frequency. The results of *Dong et al.* [1997], *Chen et al.* [1999] and *Bouille et al.* [2000] give geophysical predictions from different atmosphere, soil moisture, snow, and nontidal ocean mass data sets. The Lageos 1 and 2 solutions are from *Eanes et al.* [1997] (4 years data, 12-day interval solutions) and *Bouille et al.* [2000] (1993–1996 4-year data, monthly interval solutions). The DORIS solution is from *Bouille et al.* [2000] using 1993–1996 TOPEX/Poseidon Doppler data, monthly solutions. The GPS solution is from *Blewitt et al.* [2001] using 1996–2000 weekly network-free solutions and degree-1 deformation approach.

[44] The SLR solutions (Lageos 1 and 2) appear consistent with the geophysical predictions for both amplitudes and phases. The DORIS solutions are in good agreement with the SLR solutions, but the amplitude of  $y$  component is about 50% larger than the mean of two SLR solutions. The phases of GPS solutions are in general consistent with the others to within about 45°. The amplitudes of the GPS  $x$ ,  $y$ ,  $z$  components are about 50%, 80%, and 250% larger than in the mean SLR solutions, respectively.

[45] There are three approaches to estimate geocenter motion from GPS data analysis. The first approach uses the reference frame attached to the solid Earth to estimate degree-1 Stokes coefficients, which are proportional to geocenter positions.

[46] The second approach (network shift approach), used in the Jet Propulsion Laboratory (JPL) operational analysis, obtains free-network solutions in a CM frame, and performs a seven-parameter transformation (equation (18)) to align the solutions to ITRF. The estimated translation parameters

represent the geocenter motion and systematic errors in GPS data analysis.

[47] The third approach (degree-1 deformation approach) uses site displacement in a CF frame due to degree one mass load to infer the geocenter motion in a CM frame. The site displacement in the CF frame can be expressed as [*Blewitt et al.*, 2001]

$$\Delta X^{\text{CF}} = -I_1^{\text{CF}} J^T \text{diag}[1, 1, -2] J X_{\text{CE}}^{\text{CM}}, \quad (19)$$

where  $\Delta X^{\text{CF}}$  is the geocenter site displacement in the CF frame,  $J$  is the Jacobian matrix that converts the geocenter coordinates to topocentric (east, north, up) coordinates,  $I_1^{\text{CF}} = 0.134$  is the degree one mass load Love number under a CF frame [*Blewitt et al.*, 2001],  $\text{diag}$  represents the diagonal matrix. The geocenter motion is derived through multiplying the estimated  $X_{\text{CE}}^{\text{CM}}$  by a factor of 1.021 (see equations (7) and (8)).

[48] The  $\Delta X^{\text{CF}}$  term contains the displacements from high degree mass load harmonics, which are not completely orthogonal to that caused by degree-1 mass load. *Blewitt et al.* [2001] demonstrate that the estimated  $X_{\text{CE}}^{\text{CM}}$  is not biased significantly when we use site displacements from a globally distributed network with adequate density. Here we test the solution stability from equation (19) by introducing a modified equation (20), which adds six auxiliary parameters to absorb the site displacements from second and third degrees of mass load harmonics.

$$\Delta X^{\text{CF}} = -I_1^{\text{CF}} J^T \text{diag}[1, 1, -2] J X_{\text{CE}}^{\text{CM}} + A Y^{\text{CF}}, \quad (20)$$

where

$$A = J^T \begin{pmatrix} I_2^{\text{CE}} \frac{\partial}{\cos \varphi \partial \lambda} \\ I_2^{\text{CE}} \frac{\partial}{\partial \varphi} \\ h_2^{\text{CE}} \end{pmatrix} \cdot \begin{pmatrix} P_{20} & P_{21} \cos \lambda & P_{21} \sin \lambda & P_{22} \cos 2\lambda & P_{22} \sin 2\lambda & C_{nu} P_{30} \end{pmatrix} \quad (21)$$

$$Y^{\text{CF}} = \{y_1, y_2, y_3, y_4, y_5, y_6\}^T, \quad (22)$$

$P_{ij}$  are the unnormalized associate Legendre polynomials with degree  $i$  and order  $j$ ;  $C_{nu}$  is  $l_3^{CE}/l_2^{CE}$  for the north component and  $h_3^{CE}/h_2^{CE}$  for the up component,  $l_2^{CE}$ ,  $h_2^{CE}$ ,  $l_3^{CE}$ ,  $h_3^{CE}$  are second and third degree mass load Love numbers under a CE frame, which are the same as in a CF frame,  $\phi$ ,  $\lambda$  are latitude and longitude of the site. For internal mass load, the equations (19) and (20) should use internal mass load Love numbers.

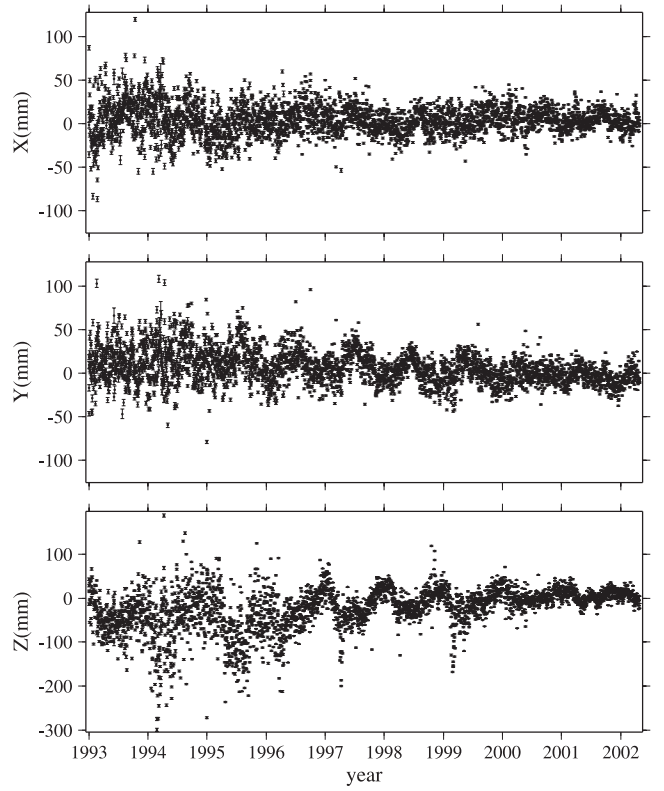
## 8. Determination of Seasonal Geocenter Motion From GPS Data

[49] Figure 2 shows the GPS geocenter time series (1993–2002.319) determined at JPL using the network shift approach. Daily free network global GPS solutions were obtained using a no-fiducial strategy [Heflin *et al.*, 1992]. The seven transformation parameters for each day were estimated by aligning the site position solutions to ITRF2000 in a least squares sense. The scatters and the amplitudes of seasonal variations of the  $x$ ,  $y$ ,  $z$  components improve with time, particularly for the  $z$  component. Both scatters and amplitudes of seasonal variations dropped significantly at 21 April 1996 and 2 April 2000. From 21 April 1996, JPL analysis began to implement ambiguity resolution. From 2 April 2000, JPL analysis performed the C1-P1 bias correction, which helped the analysis algorithm to fix more ambiguities [Jefferson *et al.*, 2001]. The ambiguity resolution reduces the correlated errors between ambiguities and all other parameters. This reduces the scatters of the estimated geocenter motion. Why this also reduces the amplitudes of geocenter seasonal variations is still an open question.

[50] Table 2 lists the estimated annual geocenter variations (network shift approach, both annual and semiannual variations are estimated) of the three intervals (1993 to 20 April 1996, 21 April 1996 to 1 April 2000, and 2 April 2000 to 27 April 2002), obtained by a robust fit to resist the influences of outliers. The phase of the  $z$  component is about  $125^\circ$  different from both the observed and predicted results in Table 1. The phase of the  $z$  component indicates that the maximum mass load in northern hemisphere is during June, which conflicts with the known time during February and March [Blewitt *et al.*, 2001]. For the geocenter time series (1993.0–2002.319), the biases and drifts at epoch 2001.0 are  $4.2 \pm 0.2$ ,  $-2.9 \pm 0.3$ , and  $3.9 \pm 0.4$  mm,  $0.1 \pm 0.1$ ,  $-2.7 \pm 0.1$ , and  $6.1 \pm 0.2$  mm/yr, for  $x$ ,  $y$ , and  $z$ , respectively. These values are likely controlled by systematic errors.

[51] We use the position time series in a CF frame from 37 globally distributed sites to estimate the geocenter motion by the degree-1 deformation approach (using equations (19) and (20)). The offsets and trends of all time series are adjusted and removed in advance. To maintain self-consistency, we discard days with fewer than 10 selected sites. Since the solution time series have no significant outliers and no dramatic changes on 20 April 1996 and 2 April 2000 (see Figure 3a), we estimate the seasonal terms for the whole interval by least squares. The estimated annual geocenter motions are listed in Table 2.

[52] The results are more consistent with SLR solutions and geophysical prediction for both amplitudes and phases (Tables 1 and 2). Our estimated annual amplitudes are about



**Figure 2.** GPS derived geocenter time series from network shift approach. The error bars represent one standard deviation.

44% (using equation (19)) and 34% (using equation (20)) smaller than that from Blewitt *et al.* [2001], but the phases are in good agreement with theirs. Our results indicate that the solutions from equation (19) are quite stable. For 37 sites, the solutions from equation (20) slightly enlarge the solutions from equation (19) owing to both limited separation capability of the estimated parameters and the influences of higher degree harmonics. If we use a denser global network, say, more than 80 sites, equation (20) may be more suitable. Figure 3a shows the geocenter time series starting from 1993.0 estimated with equation (19). Figure 3b shows the weekly average of Figure 3a.

[53] It is instructive to see a real site position time series under different frame origins. We take weekly average to the site YELL daily solutions under ITRF2000 with the secular motion being removed. The resultant time series (solid line in Figure 4) represent the nonsecular site motion under ITRF2000 and a CF frame. Assuming the degree-1 deformation approach derived geocenter motion (Figure 3b) is the ground truth, we add the Figure 3b time series (transfer to local east, north, and up direction) to the YELL time series. The results (dashed line in Figure 4) represent the nonsecular time series under a CM frame. Figure 4 clearly indicate that the realized ITRF2000 origin is not the desired frame origin (CM) on seasonal and short timescales.

[54] Here we briefly compare the network shift approach and the degree-1 deformation approach. First, the network shift approach is more sensitive to orbital systematic errors, for example, the errors in nongravitational orbital force model. The degree-1 deformation approach is biased by

**Table 2.** Estimated Annual Variations of Geocenter Motion From JPL Analysis<sup>a</sup>

	<i>x</i>		<i>y</i>		<i>z</i>	
	Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg
1993.0–1996.302 <sup>b</sup>	$6.9 \pm 0.7$	$186 \pm 6$	$8.3 \pm 0.7$	$246 \pm 5$	$31.1 \pm 1.6$	$116 \pm 3$
1996.305–2000.252 <sup>b</sup>	$3.9 \pm 0.4$	$199 \pm 6$	$11.1 \pm 0.4$	$284 \pm 2$	$25.6 \pm 0.7$	$106 \pm 2$
2000.254–2002.319 <sup>b</sup>	$4.8 \pm 0.4$	$220 \pm 5$	$3.6 \pm 0.4$	$320 \pm 7$	$9.4 \pm 0.5$	$105 \pm 3$
1993.0–2002.319 <sup>c,d</sup>	$1.7 \pm 0.3$	$227 \pm 9$	$2.8 \pm 0.3$	$306 \pm 6$	$6.5 \pm 0.3$	$228 \pm 3$
1993.0–2002.319 <sup>d,e</sup>	$2.1 \pm 0.3$	$224 \pm 7$	$3.3 \pm 0.3$	$297 \pm 6$	$7.1 \pm 0.3$	$232 \pm 3$

<sup>a</sup>Values after symbol  $\pm$  represent formal uncertainties. Amplitude and phase are defined the same as Table 1.

<sup>b</sup>Solutions from network shift approach.

<sup>c</sup>Solutions from degree-1 deformation approach using equation (19).

<sup>d</sup>Used sites are ALBH, ALGO, AREQ, BRMU, CAS1, DAV1, EISL, FAIR, FORT, GOLD, GRAZ, HART, KERG, KOKB, KOSG, MAC1, MALI, MAS1, MDO1, NALL, NLIB, ONSA, PIE1, PERT, POTS, REYK, SANT, SHAO, STJO, TID2, USUD, VILL, VNDP, WEST, WTZR, YAR1, YELL. The AREQ data after 23 July 2001 were not used due to  $M_w$  8.4 earthquake.

<sup>e</sup>Solutions from degree-1 deformation approach using equation (20).

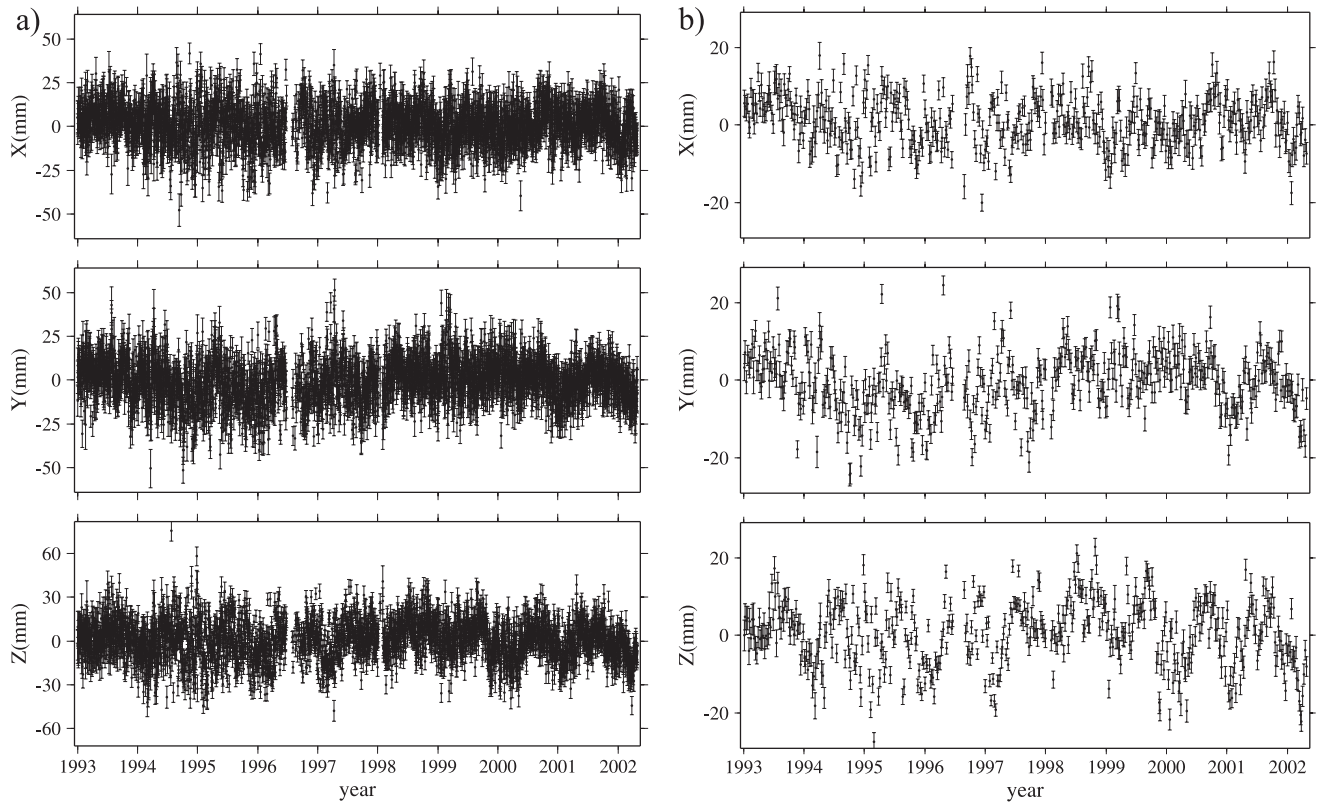
the nonmass load deformation, for example, the thermal bedrock expansion [Dong et al., 2002].

[55] Second, the VLBI data do not sense geocenter motion from network shift approach, but we still can get the geocenter motion information from VLBI data through the degree-1 deformation approach [Lavalée and Blewitt, 2002].

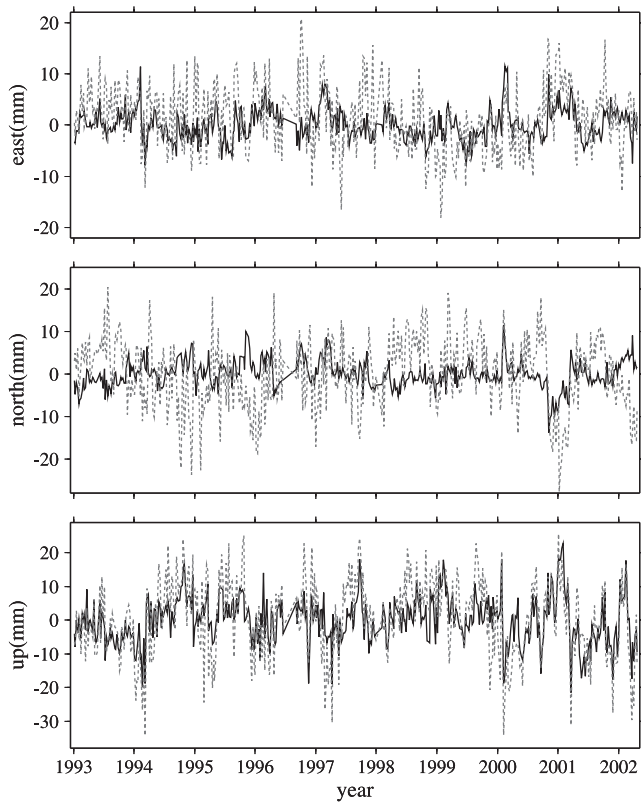
[56] Third, the degree-1 deformation approach is not sensitive to geocenter offset and drift.

[57] Figures 2 and 3 and Table 2 indicate that systematic errors common to all sites are the primary cause for the lower quality geocenter determination from the network shift approach. The last segment amplitude of the *z* compo-

nent is still larger than SLR estimates by a factor of 3 and the phase conflicts with the geophysical prediction. The *x*, *y* solutions of the last segment seem in general consistent with the SLR solutions and geophysical predictions, indicating that the unknown systematic errors mostly affect the *z* component. Thus the network shift approach appears to suffer from either strong parameter coupling or unresolved systematic errors, which affect the observed network motion as a whole, to a degree that tends to mask the subtle geocenter motion. Further research is needed to isolate the causes of this observed (and presumably spurious) whole network shift. The degree-1 deformation approach, however, supplies more reasonable estimates for both ampli-



**Figure 3.** GPS-derived geocenter time series from degree-1 deformation approach. The error bars represent one standard deviation. Note the coordinate scale is different from Figure 2. (a) Daily time series. (b) Weekly average time series.



**Figure 4.** GPS-derived YELL site position time series. Secular motion has been removed (de-trend time series). The solid line is the site position under ITRF2000 frame. The dashed line is the same site position under CM frame. The error bars are not shown.

tudes and phases, which are consistent with SLR results and geophysical predictions, although the amplitude of the  $z$  component is still larger by about a factor of 2. Thus the degree-1 deformation technique may offer a more effective means of detecting seasonal geocenter motion with GPS.

## 9. Conclusions

[58] The origin of the ITRF is currently defined as the CM. That origin maintains good stability over the long term, saying 20 years and longer [Altamimi et al., 2001, 2002]. On seasonal timescales, however, the defined origin shows several mm to 1 cm amplitude instability due to geocenter motion [Dong et al., 2002]. In recent years, the need for enhancing the stability of the reference frame on seasonal and shorter timescales has become evident. However, there is no consensus on how to reconcile the conflict between the desired nature and the realized nature of the ITRF origin.

[59] This study finds that the nature of the ITRF origin is kinematic model-dependent. The realized nature of the ITRF2000 origin resembles CM in the long term, but CF on seasonal and other short timescales. Before ITRF2000, the realized nature of previous ITRF origins was approximately CF on all timescales. Since current geocenter determinations are far from reaching satisfactory agreement, we propose to introduce a new nomenclature of the ITRF

origin to reflect its nature accurately. With such a modification, the current long-term origin stability is retained, while the stability on a seasonal timescale is improved to the submillimeter level. We incline to treat the geocenter motion as external parameters rather than embed it in site positions. This brings convenience and flexibility to meet the demands of different geoscience disciplines. At present, how to reconcile the conflict between the desired and realized natures of the ITRF origin are still open questions and the answers are probably not unique. However, such a scientific discussion is now needed and should lead to a resolution that enhances the reference frame stability on seasonal and shorter timescales.

[60] Seasonal geocenter motion is the biggest unmodeled component, and thus critical for the improvement, of the ITRF origin. Our study indicates that current GPS geocenter solutions employing the network shift approach are dominated by either parameter coupling or unresolved systematic errors, which reduce their overall quality and lead to conflicts with predictions from geophysical processes. However, the degree-1 site displacements derived from GPS are less sensitive to unresolved systematic errors. The GPS geocenter solutions derived from the degree-1 deformation approach will provide potentially valuable information on seasonal and short timescale geocenter variations. In the future, **GPS data collected from low Earth orbiters in highly inclined orbits may further improve GPS sensitivity to the  $z$  component of geocenter motion.**

[61] **Acknowledgments.** We are grateful to Richard Gross and Xiaoping Wu for helpful discussion. We would like to thank Geoffrey Blewitt, Olivier de Viron, and Associate Editor Thomas Herring for their constructive comments, which improve the manuscript substantially. The figures in this paper were generated using the public domain Generic Mapping Tools (GMT) software [Wessel and Smith, 1995]. The data and solutions of this paper are available at <ftp://sideshow.jpl.nasa.gov/pub/geo>. The research described in this paper was supported under a contract with NASA at the Jet Propulsion Laboratory, California Institute of Technology.

## References

- Altamimi, Z., et al., The terrestrial reference frame and the dynamic Earth, *Eos Trans. AGU*, 82, 273, 278–279, 2001.
- Altamimi, Z., P. Sillard, and C. Boucher, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science application, *J. Geophys. Res.*, 107(B10), 2214, doi:10.1029/2001JB000561, 2002.
- Argus, D. F., and R. G. Gordon, No-net rotation model of current plate velocities incorporating plate motion model NUVEL-1, *Geophys. Res. Lett.*, 18, 2039–2042, 1991.
- Argus, D. F., W. R. Peltier, and M. M. Watkins, Glacial isostatic adjustment observed using very long baseline interferometry and satellite laser ranging geodesy, *J. Geophys. Res.*, 104, 29,077–29,093, 1999.
- Blewitt, G., D. Lavalée, P. Clarke, and K. Nurutdinov, A new global mode of Earth deformation: Seasonal cycle detected, *Science*, 294, 2342–2345, 2001.
- Boucher, C., Definition and realization of terrestrial reference systems for monitoring Earth rotation, in *Variations in Earth Rotation*, *Geophys. Monogr. Ser.*, vol. 59, edited by D. D. McCarthy and W. E. Carter, pp. 197–201, AGU, Washington, D. C., 1990.
- Bouille, F., A. Cazenave, J. M. Lemoine, and J.-F. Cretaux, Geocentre motion from the DORIS space system and laser data on Lageos satellites: Comparison with surface loading data, *Geophys. J. Int.*, 143, 71–82, 2000.
- Chen, J. L., C. R. Wilson, R. J. Eanes, and R. S. Nerem, Geophysical interpretation of observed geocenter variations, *J. Geophys. Res.*, 104, 2683–2690, 1999.
- Dahlen, F. A., The passive influence of the oceans upon the rotation of the Earth, *Geophys. J. R. Astron. Soc.*, 46, 363–406, 1976.
- Davis, P., and G. Blewitt, Methodology for global geodetic time series estimation: A new tool for geodynamics, *J. Geophys. Res.*, 105, 11,083–11,100, 2000.

- DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, **21**, 2191–2194, 1994.
- Denis, C., Y. Rogister, M. Amalvict, C. Delire, A. Ibrahim-Denis, and G. Munhoven, Hydrostatic flattening, core structure, and translational mode of the inner core, *Phys. Earth Planet. Inter.*, **99**, 195–206, 1997.
- Dong, D., J. O. Dickey, Y. Chao, and M. K. Cheng, Geocenter variations caused by atmosphere, ocean and surface ground water, *Geophys. Res. Lett.*, **24**, 1867–1870, 1997.
- Dong, D., P. Fang, Y. Bock, M. K. Cheng, and S. Miyazaki, Anatomy of apparent seasonal variations from GPS-derived site position time series, *J. Geophys. Res.*, **107**(B4), 2075, doi:10.1029/2001JB000573, 2002.
- Eanes, R. J., S. Kar, S. V. Bettadapur, and M. M. Watkins, Low-frequency geocenter motion determined from SLR tracking (abstract), *Eos Trans. AGU*, **78**(46), Fall Meet. Suppl., F146, 1997.
- Farrell, W. E., Deformation of the Earth by surface loads, *Rev. Geophys.*, **10**, 761–797, 1972.
- Greff-Lefftz, M., Secular variation of the geocenter, *J. Geophys. Res.*, **105**, 25,685–25,692, 2000.
- Heflin, M., et al., Global geodesy using GPS without fiducial sites, *Geophys. Res. Lett.*, **19**, 131–134, 1992.
- Jefferson, D. C., M. B. Heflin, and R. J. Muellerschöen, Examining the C1-P1 pseudorange bias, *GPS Solutions*, **4**, 25–30, 2001.
- Lavallee, D., and G. Blewitt, Degree-1 Earth deformation from very long baseline interferometry measurements, *Geophys. Res. Lett.*, **29**(20), 1967, 10.1029/2002GL015883, 2002.
- McCarthy, D. D., (Ed.), IERS Conventions (1996), *IERS Tech. Note 21*, Int. Earth Rotation Serv., Obs. de Paris, Paris, July 1996.
- Minster, B., and T. H. Jordan, Present-day plate motions, *J. Geophys. Res.*, **83**, 5331–5354, 1978.
- Mueller, I. I., Reference coordinate systems: An update, in *Theory of Satellite Geodesy and Gravity Field Determination*, pp. 153–196, Springer-Verlag, New York, 1989.
- Ray, J., (Ed.), IERS analysis campaign to investigate motions of the geocenter, *IERS Tech. Note 25*, 121 pp, Obs. de Paris, Paris, 1999.
- Trupin, A. S., M. F. Meier, and J. M. Wahr, Effects of melting glaciers on the Earth's rotation and gravitational field: 1965–1984, *Geophys. J. Int.*, **108**, 1–15, 1992.
- Vigue, Y., S. M. Lichten, G. Blewitt, M. B. Heflin, and R. P. Malla, Precise determination of Earth's center of mass using measurements from the Global Positioning System, *Geophys. Res. Lett.*, **19**, 1487–1490, 1992.
- Watkins, M. M., and R. J. Eanes, Long-term changes in the Earth's shape, rotation and geocenter, *Adv. Space Res.*, **11**, 251–255, 1993.
- Watkins, M. M., and R. J. Eanes, Observations of tidally coherent variations in the geocenter, *Geophys. Res. Lett.*, **24**, 2231–2234, 1997.
- Watkins, M. M., D. F. Argus, and J. C. Ries, The use of geocenter as a kinematic reference point for large scale geophysics studies, *Eos. Trans. AGU*, **82**(47), Fall Meet. Suppl., Abstract G42A-05, 2001.
- Wessel, P., and W. H. F. Smith, New version of the Generic Mapping Tools released, *Eos Trans. AGU*, **76**, 329, 1995.

---

D. Dong, M. Heflin, and T. Yunck, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA. (Danan.Dong@jpl.nasa.gov; Michael.B.Heflin@jpl.nasa.gov; Thomas.P.Yunck@jpl.nasa.gov)