The SLR Contribution to the ITRF
Monitoring the Origin of the TRF with Space Geodetic Techniques

Erricos C. Pavlis
Joint Center for Earth Systems Technology, University of Maryland Baltimore County,
NASA GSFC Code 926, Greenbelt, MD 20771, USA

Abstract

The origin of the Terrestrial Reference System (TRS) is realized through the adopted coordinates of its defining set of positions and velocities at epoch, constituting the conventional Terrestrial Reference Frame (TRF). Since over two decades now, these coordinates are determined through space geodetic techniques, in terms of absolute or relative positions of the sites and their linear motions. The continuous redistribution of mass within the Earth system causes concomitant changes in the Stokes' coefficients describing the terrestrial gravity field. Seasonal changes in these coefficients have been closely correlated with mass transfer in the atmosphere, hydrosphere and the oceans. The new gravity-mapping missions, CHAMP and GRACE, and to a lesser extent the future mission GOCE, address these temporal changes from the gravimetric point of view. For the very low degree and order terms of the gravity field model, this gravity or dynamic effect also manifests itself as a geometric effect that affects the origin and orientation relationship between the instantaneous and the mean reference frame. Satellite laser ranging data to LAGEOS-1 and -2 contributed the most accurate geocenter observations yet, demonstrating millimeter level accuracy for weekly averages. Other techniques, like GPS and DORIS, have also contributed and continue to improve their results with better modeling and more uniformly distributed (spatially and temporally) tracking data. We present the results from the various techniques, assess their accuracy and compare them. We also look into potential improvements in the future, which will likely lead us to even finer resolution and higher accuracy through the constructive combination of the individual time series.

Introduction

The center of mass of a distribution of masses M described in a Cartesian coordinate frame (*x, y, z*) is defined from mechanics as the point with coordinates (x_c, y_c, z_c):

$$x_c = (1/M) \iiint x' dM$$
$$y_c = (1/M) \iiint y' dM \qquad (1)$$
$$z_c = (1/M) \iiint z' dM$$

In the case of Earth, the total mass comprises all components that make up the "Earth system", i.e., the solid Earth, the atmosphere, the oceans, and the hydrosphere (cryosphere, ice-packs, rivers, lakes, soil moisture, etc.). These components possess a "mean" state and a circulation with a rich and varying spectrum. The circulation of mass within this system results in a continuous redefinition of the "center of mass" of the system as defined by (1), which we will call "geocenter" for brevity. The reference frame used to describe positions is nowadays established by space techniques, such as Satellite Laser Ranging (SLR), the Global Positioning System (GPS), Doppler

Orbitography Radiopositioning Integrated by Satellite (DORIS), and Very Long Baseline Interferometry (VLBI). Only satellite techniques are sensitive to the location of the geocenter relative to the tracking station network. Over the last decade, some of these techniques have monitored the motion of the geocenter as a time series of deviations from the mean location realized by the center of figure of the tracking network. SLR is the technique with the highest resolution and most accurate results to date, with the GPS and DORIS techniques making steady advances towards a significant contribution in this climate-change-monitoring process.

Geophysically Driven Motion of the Geocenter

The global observational data sets that are collected through ground and space-borne instruments require a well-defined, stable reference frame to be reported in for subsequent evaluation, cross-referencing and interpretation. The natural choice for the origin of that reference frame is the geocenter since it is not only the instantaneous "center of mass" of the system, but it is also a point that can be physically realized through the precise orbits of artificial satellites. It is thus important to not only be able to establish this origin at some point in time, but to also be able to describe its temporal variations for as long as we want to maintain the invariability of our reference frame. This is where mass redistribution in the Earth system enters the picture. It is the cause of the observed motion of the geocenter, thereby a source of uncertainty in the definition of the frame of reference for any type of geophysical data. The Earth system is a very complex one, and we are only now getting to understand the finer aspects of the complicated interaction of its many components, as Figure 1 illustrates.

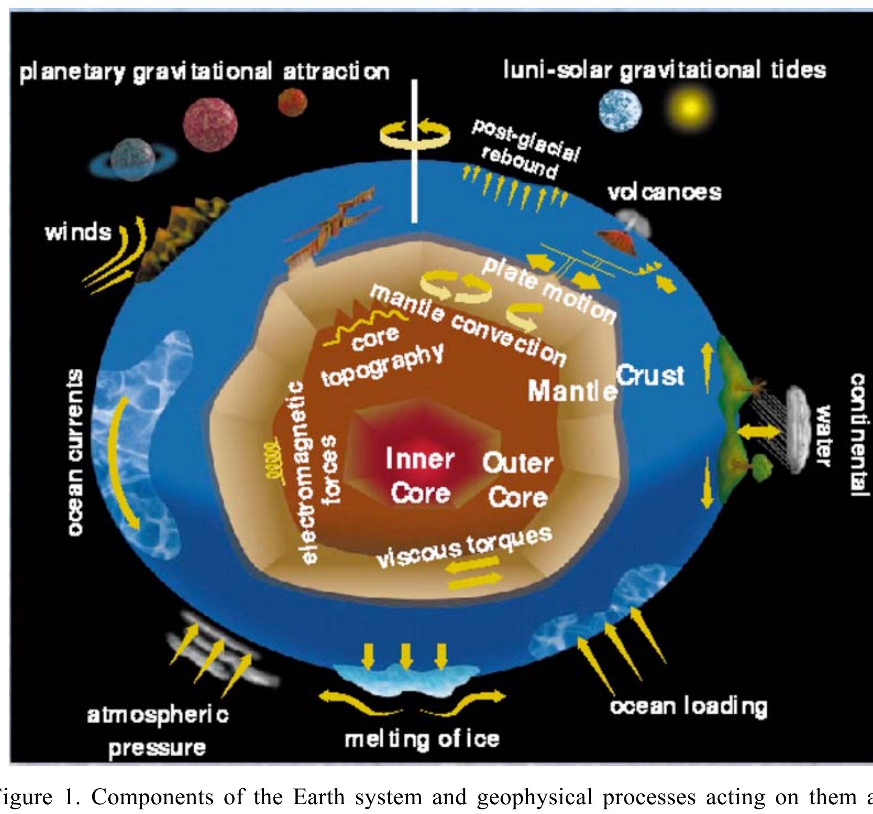

Figure 1. Components of the Earth system and geophysical processes acting on them and interacting with them (after Lambeck, graphic by Verheijen).

Since the fluid components of the Earth system are not distributed symmetrically over the solid part of the planet, the circulation within each of these as well as the interaction amongst them, create a complex, constantly changing "shell" of mass, which in turn causes the geocenter to "gyrate" about a mean position with a rather random motion. Naturally, since weather has a lot to do with the circulation patterns, one expects to find certain signals in this motion, such as annual, semi-annual and seasonal, and this is indeed the case as it is illustrated in Table 1. With more space-borne remote sensing instrumentation providing global snapshots of the fluid envelope of Earth with high temporal and spatial resolution, it is now possible to observe this mass distribution and compute the equivalent shifts it will cause in the geocenter location. This is already achievable for some of the geophysical fluids, to a certain resolution and accuracy. We are still however very far from having a complete and accurate picture of this motion from all sources and we thus have to monitor the total effect through direct observations by means of space geodetic techniques.

Table 1. Annual and semi-annual signals in the geocenter driven by geophysical fluids motions (adapted from *Johnson et al.*, [2001]).

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Table 3. Geocenter Motion Seasonal Sinusoids Computed From the Combined Analysis of LAGEOS I and II Satellites, Atmosphere, Ocean, and Continental Water Storage[a]

		Annual		Semi-Annual	
Source	Axis	Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg
Atmosphere (IB)	x	0.55	104	0.23	90
ECMWF	y	1.31	91	0.38	217
Dong et al. [1997]	z	0.87	133	0.73	271
Atmosphere (IB)	x	0.40	165	0.30	270
GEOS-1	y	1.35	150	0.47	335
This paper	z	0.44	134	0.70	353
Oceans (ISO Model)	x	1.05	79	0.39	248
Dong et al. [1997]	y	0.09	121	0.29	282
	z	0.18	218	0.16	41
Oceans (T/P Model)	x	0.96	73	0.86	187
Chen et al. [1998]	y	0.97	52	0.73	173
	z	0.49	3	0.25	232
Oceans (POCM_4B)	x	0.89	92	0.24	117
No correction	y	0.40	130	0.23	22
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Sea level adjustment	y	0.40	136	0.24	23
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Continental Hydrology	x	3.28	25	0.84	319
Dong et al. [1997]	y	2.94	185	0.94	48
	z	3.57	40	0.60	344
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(CDAS-I)	y	0.52	182	0.56	312
Chen et al. [1999]	z	3.30	43	0.50	75

Observational Approach of the Geocenter Motion

There are two approaches to monitor the motion of the geocenter with space geodesy. The geometric approach was historically the first one to be used, since high uncertainties in the force models prohibited us from using the other method (dynamic), which requires very precise orbit determination.

The geometric approach consists of a direct comparison of short-term estimates of the network positions (e.g., monthly, bi-weekly, or weekly) with respect to a standard set of positions, usually derived from a much longer averaging period (e.g., several years). As it is discussed in [*Pavlis*, 1999], the geometric technique, which amounts to estimating the three Cartesian offsets as part of a seven-parameter similarity transformation (also known as Helmert transformation), is very sensitive to changes in the tracking network. This is understandable since stations can be inoperable at times due to repairs or upgrades and in the case of SLR, due to poor weather. This peculiarity in the sensitivity of each technique introduces slight differences in the derived estimates, which however are below their formal accuracy.

On the other hand, the dynamic approach smoothes over such variations using the orbit as a filter. The dynamic approach relies on the estimation of the degree-one terms of the spherical harmonic expansion of the gravitational potential, which are directly proportional to the sought-for geocenter offsets [*Heiskanen and Moritz*, 1967]:

$$\begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} = a_e \sqrt{3} C_{0,0} \begin{Bmatrix} \Delta C_{1,1} \\ \Delta S_{1,1} \\ \Delta C_{1,0} \end{Bmatrix} \tag{2}$$

where C_{nm} and S_{nm} are the un-normalized spherical harmonic coefficients and a_e is the semi-major axis of the ellipsoid associated with the gravitational model. It is undoubtedly very important that the force modeling for the utilized satellites/targets be of the utmost quality, since any mis-modeled effect will easily find its way in the estimated geocenter offsets. In that respect, the improvement of the accuracy of the gravitational models from missions such as CHAMP, GRACE and GOCE, will soon help eliminate any significant uncertainties in these models.

There are other effects also that "contaminate" the geocenter motion estimates since we are still not able to account fully for these effects in our estimation process. Indicative levels of such errors are shown in Table 2. Most of these are well below our level of sensitivity today, so they are lumped in the noise of the estimates now. We should not forget them though, as they will soon start reaching up when the new models become available.

Table 2. Sources of variation and their effect in the motion of the geocenter.

Source	Magnification	Induced Motion	Ref.
Sea level	~1.2 mm/y	0.064±0.02 mm/y	[2]
Ice sheets (G)	2 mm/y	0.046±0.20 mm/y	[2]
Tectonics	AMO-2	0.309±0.05 mm/y	[2]
Postglacial rebound	ICE-3G model	0.2 – 0.5 mm/y	]1]

[1] : *Greff-Lefftz* [2000]
[2] : *Barkin* [1997]

State-of-the-Art Observations from Space Techniques

The first time series of geocenter motion were developed in the mid-90's in connection with an IERS campaign [*Ray* (ed.), 1999]. Several SLR, DORIS and GPS analysis groups generated series that were intercompared and examined for coherence. Results from this campaign were later extended, improved and compared to time series of geophysical signals generated from global circulation models or derived from independently collected data [*Dong et al.*, 1997], [*Chen et al.*, 1999], [*Pavlis*, 2001].

In recent years, all of the satellite techniques produce at least one variant of geocenter motion time series. SLR series of weekly estimates from JCET/GSFC (Figure 2) are routinely generated since 1996, based on LAGEOS and LAGEOS-2 data. The Center for Space Research at the University of Texas at Austin produces a 12-day average series based on LAGEOS and LAGEOS-2 data also (Figure 3, left), and a monthly average series in combination with SLR data from TOPEX/Poseidon (Figure 3, right). They also generate a "hybrid" series of monthly averages, combining the last one along with DORIS data collected also on TOPEX/Poseidon (Figure 4, left). The DORIS data are also used by the CNES research group to generate similar, but purely DORIS-based series (Figure 4, right).

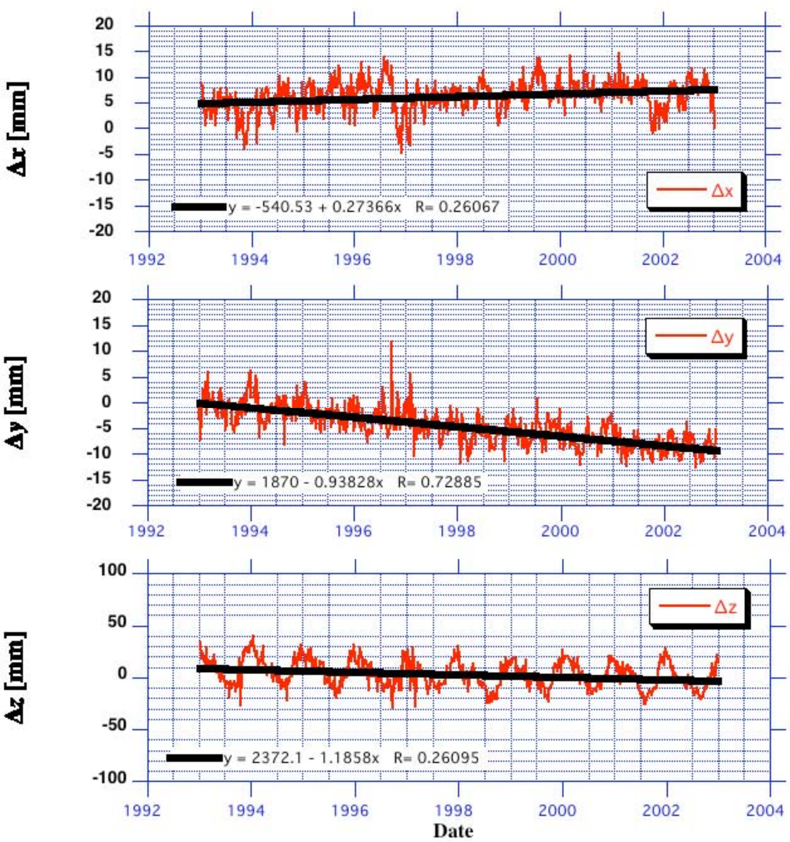

Figure 2. JCET/GSFC weekly average geocenter offsets based on the analysis of LAGEOS and LAGEOS-2 SLR data over 1993.0 - 2003.0 (Note: these are total variations, including trends).

The solutions that have been generated with GPS data have always suffered from increased noise levels and transient signals that are not seen by the other techniques. Individual analysis centers (ACs) produce their own daily solutions (e.g., on the left side of Figure 5, from the Jet Propulsion Lab –JPL, AC), however, these series are still exhibiting a significantly larger variation than what is seen in the SLR and DORIS series, or even in the weekly mean series from the IGS combination center (Figure 5, right).

Most of the examined series display some periodic signals of some sort, however, obvious coherence amongst them is very poor, at least at first glance. When the annual and semi-annual signals are estimated, the comparison is far more promising and in fact, one can even see some agreement in amplitude and phase with the corresponding signals estimated from purely geophysical data or models (Table 3).

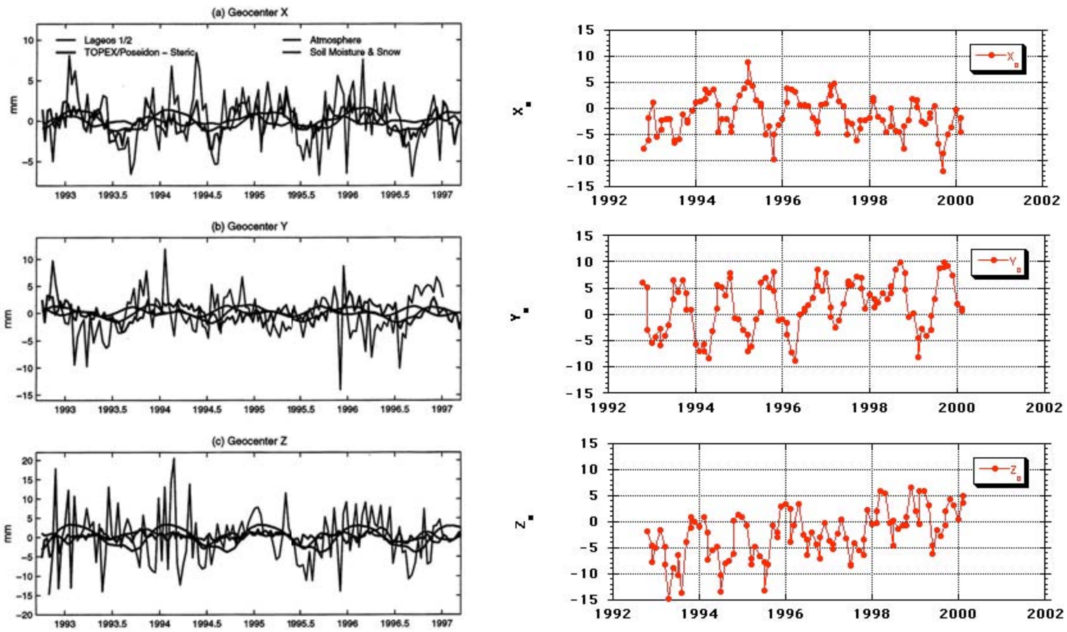

Figure 3. The CSR/UTEX 12-day (left) and monthly (right) series of observed geocenter components from LAGEOS-1 and -2 solutions, along with atmospheric, continental hydrological and oceanic contributions [Chen et al., 1999].

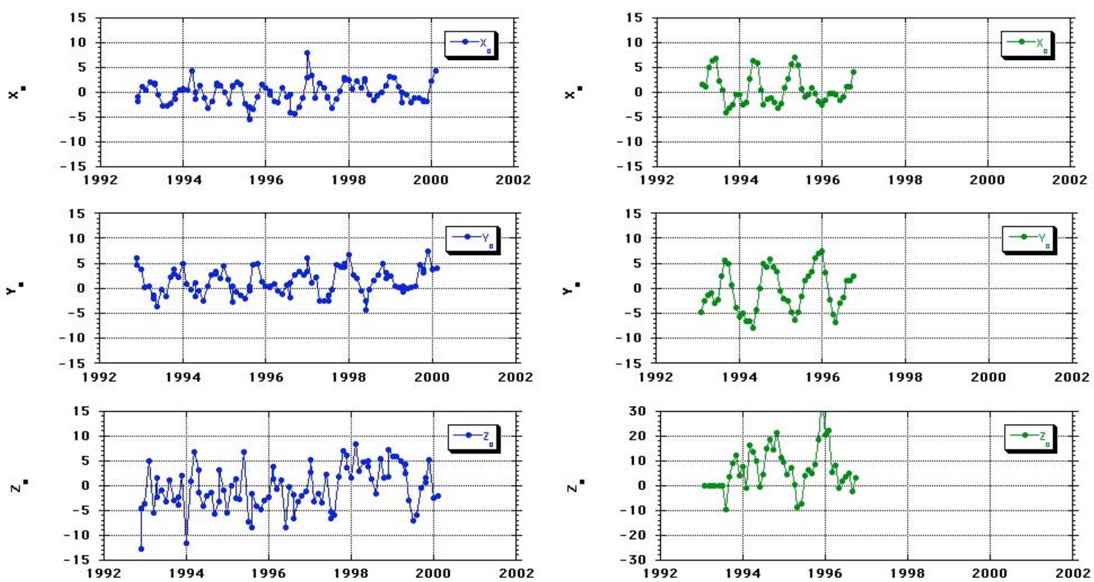

Figure 4. The monthly mean geocenter series from CSR/UTEX (left) based on the combined reduction of SLR and DORIS data, and from CNES (right), from DORIS data alone (note scale change for z-component of CNES).

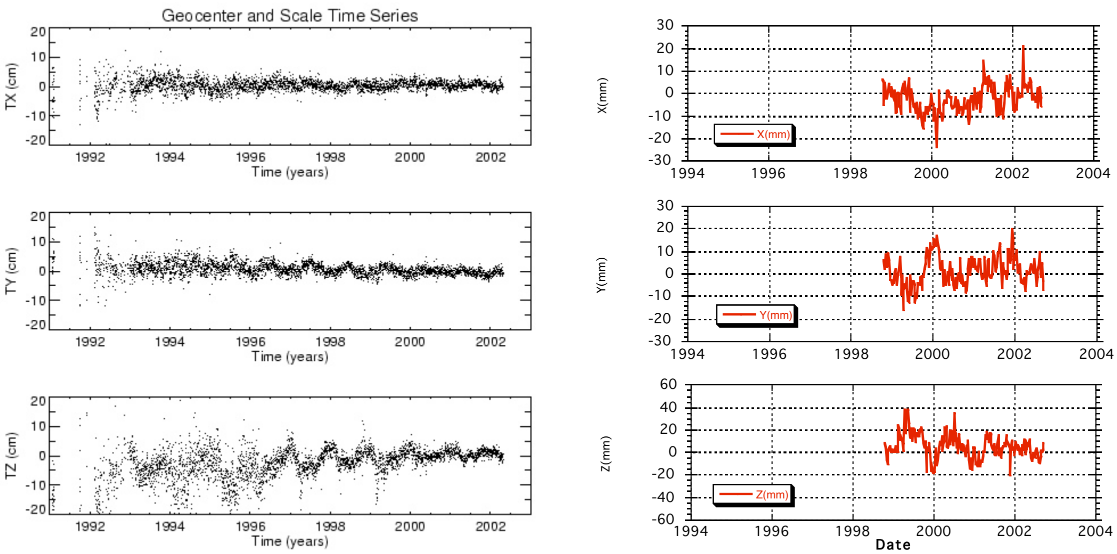

Figure 5. The daily mean geocenter series from JPL (left, in cm) based on the reduction of GPS data from the global IGS network, and the weekly mean estimates from the IGS Analysis Coordination Center (right, in mm) [*Ferland, R.*, 2003].

Table 3. Annual and semi-annual signals in the geocenter, driven by geophysical fluids motions, and SLR-derived observed signals for comparison (adapted from *Johnson et al.*, [2001]).

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		Annual		Semi-Annual	
Source	Axis	Amplitude, mm	Phase, deg	Amplitude, mm	Phase, deg
LAGEOS I/II Solution	x	2.18	31	1.08	164
Eanes et al. [1997]	y	3.20	151	0.77	213
	z	2.79	45	0.38	13
Sum Oceans (POCM_4B-	x	1.88	76	0.16	287
SLA)+Atm (GEOS-1)+	y	2.19	158	1.15	333
Hydro. [*Chen et al.*, 1999]	z	3.18	51	0.83	28
Sum Oceans (POCM_4B-	x	3.42	43	0.83	312
SLA)+Atm (GEOS-1)+	y	4.44	171	1.41	25
Hydro. [*Dong et al.*, 1997]	z	3.43	47	1.21	348
Sum Oceans (POCM_4B-	x	2.36	72	0.38	83
SLA)+Atm (ECMWF)+	y	1.78	118	0.62	298
Hydro. [*Chen et al.*, 1999]	z	3.28	59	0.26	282
Sum Oceans (POCM_4B-	x	3.90	45	0.56	350
SLA)+Atm (ECMWF)+	y	3.50	158	0.79	46
Hydro. [*Dong et al.*, 1997]	z	3.49	54	1.03	299
Atmosphere (IB)	x	0.55	104	0.23	90
ECMWF	y	1.31	91	0.38	217
Dong et al. [1997]	z	0.87	133	0.73	271
Atmosphere (IB)	x	0.40	165	0.30	270
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[a] The amplitudes are in units of millimeters and the phases are in units of degrees from January 1 using a sine convention.

Conclusions

All three satellite positioning techniques, SLR, DORIS and GPS, have demonstrated that they are sensitive to the motion of the geocenter to varying degrees. Estimates of this motion with different resolution and accuracy have been published to date from all techniques and in most cases there are even inter-technique comparisons, as well as comparisons with independent, purely geophysical estimates of this motion.

It is in general agreed that the peak-to-peak motion of the geocenter is only a few millimeters in the two equatorial components *x* and *y*, with slightly higher amplitudes, approaching the centimeter in the case of the *z* component. Although the accuracy estimates of these components is at the 2-3 mm level, the differences between estimates from various techniques well exceed these errors, in fact in certain cases by an order of magnitude.

As a first approximation to the solution of the problem the equivalence of a geometric and a dynamic approach has been shown early in the game. There are however several deficiencies in our current modeling of the physical process, including the indirect, loading effect, which has been recently observed by GPS [*Blewitt et al.*, 2001], that warrant a fresh look at the adopted models. As the new geopotential mapping missions, such as CHAMP, GRACE, and in the near future GOCE, start producing higher spatiotemporal resolution gravity models, we will soon be forced to extend these models to include a complete description of the geocenter motion, since all of the neglected terms will be entering the picture. The new modeling should follow closely the physics of the problem, rather than the geometrically intuitive simple Helmert transformation approach. The synergistic combination of geometry and dynamics will only help strengthen the estimates, through the improved sensitivity estimates of the observations.

Acknowledgments

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References

Barkin, Y.V., Secular effects in the geocenter motion, *Eos Trans. AGU, 78(46)*, Fall Meet. Suppl., F145, 1997.

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

Chen, J.L., C.R. Wilson, R.J. Eanes and R.S. Nerem, Geophysical interpretation of observed geocenter variations. *J. of Geophys. Res.,* 104, B2, pp. 2683-2690, 1999.

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, pp. 1867–1870, 1997.

Ferland, R., Reference Frame Working Group Report, International GPS Service, 2001 Technical Report, JPL publication 03-xx, in preparation, 2003.

Greff-Lefftz, M., Secular variation of the geocenter, *J. of Geophys. Res.,* 105, B11, pp. 25685-25692.

Heiskanen, W.A., and H. Moritz, (1967), Physical Geodesy, W.H. Freeman and Company, San Francisco and London, 1967.

Pavlis, E.C., Fortnightly Resolution Geocenter Series: A Combined Analysis of LAGEOS 1 and 2 SLR Data (1993-96), in *IERS Technical Note 25*, Observatoire de Paris, Paris, France, 1999.

Pavlis, E.C., Dynamical Determination of Origin and Scale in the Earth System from Satellite Laser Ranging, in *Vistas for Geodesy in the New Millennium*, Proceedings of the 2001 International Association of Geodesy Scientific Assembly, Budapest, Hungary, September 2-7, 2001, J. Adam and K.-P. Schwarz (eds.), pp. 36-41, Springer-Verlag, New York, 2002.

Ray, J. (Ed.), IERS Analysis Campaign to Investigate Motions of the Geocenter, *IERS Technical Note 25*, Observatoire de Paris, Paris, France, 1999.