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IERS Analysis Campaign to Investigate Motions of the Geocenter

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IERS Technical Notes

This series of publications gives technical information related to the IERS activities, e.g., reference frames, excitation of the Earth rotation, computational or analysis aspects, models, etc. It also contains the description and results of the analyses performed by the IERS Analysis Centres for the Annual Report global analysis.

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- No 22: C. Reigber and M. Feissel (eds.). IERS missions, present and future. Report on the 1996 IERS Workshop
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In preparation

- No 26: D. Salstein, B. Kolaczek, D. Gambis (eds.). El Niño, Earth rotation, and related phenomena.

FOREWORD

Resolution No. 2 of the IUGG (1991) and the *IERS Conventions 1996* recommend that the origin of the terrestrial reference system be “the geocenter of the Earth's masses”, including oceans and atmosphere. It is realized by observations of the dynamics of satellites moving in the Earth's gravitational field. However, analyses of satellite laser ranging (SLR) data have strongly indicated that the coordinate frame of tracking stations attached to the Earth's crust moves detectably relative to the Earth's center of mass. This translational motion, when viewed from a rigid crust-fixed frame, is known as “geocenter motion” and is caused by the mass movement of planetary fluids, primarily the atmosphere and oceans. The motions likely involve tidal, non-tidal, and secular components.

In view of this phenomenon, time-varying (albeit small) translational motions are inevitable between the Earth's center of mass and the origin of the International Terrestrial Reference Frame (ITRF), which has implicitly been realized as a time-averaged geocenter position. It is the responsibility of the IERS to be prepared to coordinate observations and distribute appropriate results to monitor geocenter motions when that is feasible. In this way users would be able to accurately account for the instantaneous vector offset of the geocenter from the ITRF origin, much like the Earth orientation parameter service already provided by the IERS.

Before embarking on such an ambitious expansion of IERS responsibilities, however, a better understanding is needed of the magnitude of geocenter motions and of the current ability of the observing techniques to measure the effects. To address this matter, the IERS, during its 1996 Workshop, asked the IERS Working Group on the ITRF Datum to conduct an investigative campaign. A call for participation was issued in January 1997 for the *IERS Analysis Campaign to Investigate Motions of the Geocenter*. At least 42 individual researchers from more than 25 groups responded with proposals to analyze satellite tracking data for both tidal and non-tidal signals, to analyze data for geophysical excitations (including oceanic, atmospheric, and other fluid motions), and to compare and synthesize the analysis results. The activities of the Campaign have been published and distributed at the Web site <http://maia.usno.navy.mil/geoc.html> and an e-mail exploder was created to promote interaction among the participants.

The Campaign culminated in a special session at the Fall 1997 AGU Meeting in San Francisco. The overall impression of the work presented there was that the net motion of the terrestrial reference frame relative to the Earth's center of mass is detectable but small, probably no more than ~1 cm in any component. The diurnal and semi-diurnal tidal variations appear to be well determined and in good agreement with modern ocean tidal models. There seems to be some general agreement of the techniques in detecting seasonal variations, although more work remains to be done in this area. Geophysical computations of the expected motions based on global fluid motions are only roughly consistent with the observations. It was agreed by the participants that their reports would be collected into this IERS Technical Note.

As a result of the Geocenter Campaign, the following set of recommendations, subsequently modified, was adopted and presented to the IERS Directing Board:

1) A tidal model for the diurnal and semi-diurnal geocenter motions should be adopted based on an ocean tide model such as CSR3.0 (M. Watkins & R. Eanes, *Geophys. Res. Lett.*, **24**(17), 2231-2234, 1997). This model should be included in the next edition of the *IERS Conventions*. Suggestions to include the geocenter effect into the standard ocean loading coefficients, as a convenience for some users, are *not* recommended as this could lead to confusion.

2) Because the satellite techniques do not yet seem reliable for measuring variations at other frequencies, a simple seasonal model should be investigated for the principal non-tidal motions. Such an empirical model could be based on a weighted combination of the analysis results, similar to the procedure described by H. Montag. However, results currently available do not yet justify recommending such models for general use. The IERS terrestrial reference frame section at the Institut Géographique National is asked to continue studies of this type to evaluate future improved observational data and analysis methods.

3) General geocenter monitoring can be continued in two ways: the new IERS coordinating center for Monitoring of Global Geodynamical Fluids (MGGF) will have a subcenter devoted to computing offsets of the ITRF origin from the geocenter due to large-scale fluid motions; and the ITRF section will soon begin to compute monthly realizations of the terrestrial frame which can be compared with the fluid motion effects. When detection of non-tidal geocenter motions appears feasible the situation can be reassessed.

The members of the IERS Working Group on the ITRF Datum, which has sponsored this Campaign, have been Geoff Blewitt, Claude Boucher, Richard Eanes, Martine Feissel, Mike Helfin, Tom Herring, Jan Kouba, Chopo Ma, Horst Montag, Jim Ray, and Pascal Willis. The following corresponding members have made valuable contributions to the Campaign and the efforts of the Working Group: Zuheir Altamimi, Marshall Eubanks, Gerard Petit, John Ries, Hans-Georg Scherneck, and Patrick Sillard.

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IERS Working Group on the ITRF Datum

SECULAR EFFECTS IN THE MOTION OF THE EARTH'S CENTER OF MASSES

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1. INTRODUCTION

All the processes of Earth's mass redistribution affect the position of its center of masses (ECM). Drift of the ECM is generated by slow (secular) mass redistributions*. Secular effects in the ECM motion can be affected by processes of mass redistribution in the Earth's envelopes, or between them, as well as by global motions and changes of these dynamically nonspherical Earth's envelopes.

The main processes we will refer to are:

(1) sea level change, (2) ice sheet changes (Greenland ice sheet, Antarctic ice sheet) and in general Earth's ice-water envelope change (including glaciers, the ground water and others); (3) tectonic displacements and motion of the crust masses (postglacial rebound, plate motion, subduction and mass accumulation of the dipping oceanic areas of the plates and others); (4) plume and magma motion from the fluid core to the Earth's crust; (5) mantle flows and formation of heterogeneities in the mantle; (6) heterogeneities' motion in the fluid core; (7) slow atmospheric changes due to climatic secular changes.

Other processes we refer to are: (8) global rotation of the lithosphere (and other Earth's envelopes) as an asymmetric body; (9) translatory-rotary motion of the rigid core; (10) displacements of the center of masses of the mantle, fluid core, and other Earth's envelopes. The last three processes define the geological life and history of the Earth.

Thus, the list of the processes and phenomena that characterize and determine slow ECM displacements is long, but the role of each of them can be studied separately. Therefore, in this work we will concentrate on the analysis of the most important processes: ice-water mass redistributions and apparently the slowest processes of tectonic-mass redistribution, namely we will consider the eventual role of subduction and accumulation of masses of submerging oceanic plates.

All the above processes are not infrequently in mutual counteraction, their action variously manifests in different geological epochs, sometimes they compensate one another.

2. SECULAR EFFECTS CAUSED BY ICE-WATER MASSES REDISTRIBUTIONS IN THE PRESENT EPOCH

Let us first make some preliminary estimates of the parameters of the ECM drift due to changes of the sea level and ice sheets of Greenland and Antarctic in the present epoch. In previous papers on the given problem (Farell and Clark, 1976; Wu and Peltier, 1984) some effects of the ice melting of Greenland and Fennoscandia have been studied. Elastic and viscous-elastic Earth's models have been considered in these papers.

Monthly mean sea level observations at 655 tide gauge stations distributed worldwide indicate that the eustatic sea level has been rising at a rate of $\dot{\zeta}_0 = 1.15 \pm 0.38$ mm/yr during the last 80 years (Nakiboglu and Pointon, 1986). This indicates that the volume of ocean water has been increasing by 420 km³/yr during this period of time.

* In principle, the slow change in the center of mass position can be generated also by quick visco-elastic deformations of the Earth's envelopes, for example, due to lunar-solar tides.

The present mass balance estimates of Greenland and Antarctic ice sheets indicate no melting but an ongoing accretion at respective rates of $\dot{z}_G = (2 \pm 8)$ cm/yr and $\dot{z}_A = (2 \pm 2)$ cm/yr. The corresponding changes in eustatic sea level are $\dot{\zeta}_G = (-0.1 \pm 0.4)$ mm/yr and $\dot{\zeta}_A = (-0.6 \pm 0.6)$ mm/yr due to Greenland and Antarctic ice accumulation respectively (Koomanoff, 1985). Significant errors of the above characteristics of course do not allow us to say with confidence about a real ice-water balance.

It is recognized that one of the plausible causes of the observed eustatic rise of the ocean level is the secular warming of climate. The global surface air temperatures have increased by about 0.4°C during the past century (Gornitz et al, 1982). Eustatic rate of the sea level change induced by thermal expansion is estimated as $\dot{\zeta}_w = 0.8$ mm/yr (Meier, 1984). Although there are some alternative views of the problem, according to which thermal expansion of the ocean is not the principal contribution to the sea level change (Singer, 1997).

One of the major contributions to the sea level rise comes from melting glaciers. This process leads to a sea level rise at a rate of $\dot{\zeta}_{GL} = 0.40$ mm/yr.

In our paper we will use the simplest model for processes of transformation and redistribution of the ice-water masses of the Earth. We will consider homogeneous and eustatic changes of the sea level and ice sheets ongoing on the rigid surface of the Earth.

Obviously, in the southern hemisphere of the Earth the ocean occupies larger areas. It means that as the sea level is rising the ECM will move southward. Accretion of the Antarctic ice sheet produces a similar effect on the ECM motion. Accretion of the ice masses of the Greenland sheet will partially compensate the above effect.

Thus, the rate of the sea level change is

$$\dot{\zeta} = \dot{\zeta}_G + \dot{\zeta}_A + \dot{\zeta}_w + \dot{\zeta}_{GL} \quad (1)$$

In accordance with what was said, in this paper we will use the following numerical values of the corresponding components of the sea level change:

$$\begin{aligned} \dot{\zeta} &= 1.15 \frac{\text{mm}}{\text{yr}}, \quad \dot{\zeta}_w = 0.80 \frac{\text{mm}}{\text{yr}}, \quad \dot{\zeta}_{GL} = 0.40 \frac{\text{mm}}{\text{yr}} \\ \dot{\zeta}_A &= -0.04 \frac{\text{mm}}{\text{yr}}, \quad \dot{\zeta}_G = -0.01 \frac{\text{mm}}{\text{yr}} \end{aligned} \quad (2)$$

Values of $\dot{\zeta}_A$ and $\dot{\zeta}_G$ in (2) were obtained from the balance equation of the ice-water masses of the Earth.

Data (2) mean that the actual accumulation of the ocean masses is characterized by a rate of $\dot{z}_0 = 0.35$ mm/yr. Accretion rates of the Antarctic and Greenland sheets are $\dot{z}_A = 1.26$ mm/yr and $\dot{z}_G = 1.69$ mm/yr, respectively. Average rate of decrease of the glaciers and ground water is adopted here to be $\dot{z}_{GL} = -1.11$ mm/yr.

For a thin spherical layer of uniformly accreted masses (ice or water) with density ρ_0 on a certain Earth's surface σ , the components of the ECM velocity in the Earth's reference system of a given epoch are defined by the following surface integrals:

$$\begin{aligned}
\dot{x}_C &= \frac{\rho_\sigma R^3}{m} \dot{z}_\sigma \oint\!\!\!\oint_\sigma \cos^2 \varphi \cos \lambda \, d\varphi \, d\lambda \\
\dot{y}_C &= \frac{\rho_\sigma R^3}{m} \dot{z}_\sigma \oint\!\!\!\oint_\sigma \cos^2 \varphi \sin \lambda \, d\varphi \, d\lambda \\
\dot{z}_C &= \frac{\rho_\sigma R^3}{m} \dot{z}_\sigma \oint\!\!\!\oint_\sigma \cos \varphi \sin \varphi \, d\varphi
\end{aligned} \tag{3}$$

Here φ, λ are spherical coordinates of the elementary surface elements $d\sigma$ (φ is latitude, λ is longitude), m and R are mass and radius of the Earth, $\dot{z}_\sigma$ is rate of mass accretion of the corresponding thin growing layer. Integration in (3) is extended to the surface occupied by sea or corresponding ice sheets.

When calculating integrals (3), the real particularities of the surface σ boundaries were taken into account. As a result, we obtained the following general formulae for the components of the ECM velocity (3) (w.r.t. geocentric Greenwich reference system of the given epoch):

$$\begin{aligned}
\dot{x}_C &= -0.02929\dot{z}_0 + 0.00049\dot{z}_G - 0.00031\dot{z}_A + 0.02911\dot{z}_{GL} \\
\dot{y}_C &= -0.02948\dot{z}_0 - 0.00044\dot{z}_G + 0.00075\dot{z}_A + 0.02917\dot{z}_{GL} \\
\dot{z}_C &= -0.03700\dot{z}_0 + 0.00222\dot{z}_G - 0.01258\dot{z}_A + 0.04736\dot{z}_{GL}
\end{aligned} \tag{4}$$

We emphasize that the parameters in (4) characterize real secular growing or decay of the masses along the corresponding surface σ . Using the above values for these parameters, with equation (4) we obtain the following conclusion.

1. Due to ice-water masses' redistribution of the Earth, glacier melting, growth of the Antarctic and Greenland ice sheets, and mass accumulation in the sea, the center of masses of the Earth is moving at a velocity of 0.49 cm/cy in the direction SE.

It is worth noting that the derived velocity is very sensitive to the model parameters. Taking into account a big spread in values of components (2) of the rate of the sea level rise as given by different authors (Meier, 1984; Nakiboglu and Pointon, 1986; Whar et. al., 1993; Singer, 1997), our estimates should be considered as crude and preliminary or as some numerical examples.

With more certainty we can say about directions of the ECM displacements due to each of the mechanisms considered separately. Using formulae (4) and values (2), we come to the following conclusions.

1.1. Due to growth of the ocean masses at a rate of $\dot{z}_0 = 0.35$ mm/yr, the ECM is moving toward the geographic point 41°.7 S, 134°.8 E (in the south of the Pacific Ocean) at a velocity of 1.95 mm/cy.

1.2. Due to accretion of the ice masses of the Greenland sheet at a rate of $\dot{z}_G = 1.69$ mm/yr, the ECM is moving at a velocity of 0.39 mm/cy in the direction 73°.0 N, 40°.1 W (toward the island center).

1.3. Due to accretion of the ice masses of the Antarctic sheet at a rate of $\dot{z}_A = 1.76$ mm/yr, the ECM is moving at a velocity of 1.59 mm/cy in the direction 86°.3 S, 112°.4 W (toward the Antarctic center).

3. ON THE DISPLACEMENT OF THE EARTH'S CENTER OF MASSES IN THE POSTGLACIAL PERIOD

Here, on the basis of the simplest transformation model of the northern and southern ice caps of the Earth and corresponding rise of the sea level in the last postglacial period, some possible effects in the ECM motion are studied.

The latest postglacial epoch began about 8,000 years ago. It was preceded by the last glaciation (115,000 years ago to 10,000 years ago). The maximum of glaciation was about 18,000 years ago and ended about 8,000 years ago.

The known data about redistribution of the ice masses in these epochs and character of sea level variation allow us to estimate the parameters of the ECM displacement due to melting of glaciers and sea level change on the basis of the results obtained in section 2 [formula (4)]. In this paper, we will consider only the 10,000-year period (t_0 , t) of intensive sea level change which follows immediately after the period of maximal glaciation (t_0) to the epoch of the beginning of the new postglacial period (t). During this period, the sea level rose by 125–130 meters; this was established and confirmed by different methods (geological and isotopic) (Barkov et al., 1997). The mean rate of sea level rise in this period was quite considerable and constituted $\dot{z}_0 = 12.5$ mm/yr. It is much greater than the modern value of $\dot{z}_0$.

We will use the known data about distribution and structure of the ice masses of the Pleistocene ice sheet (Donn et. al., 1962; O'Connell, 1971, and others).

According to these data, the ice volumes of Greenland and Antarctic sheets (or of the northern and southern ice caps of the Earth) at epoch t_0 are estimated as $65 \cdot 10^6$ km³ and $35 \cdot 10^6$ km³. At the present epoch (t), the volumes of these sheets constitute $3 \cdot 10^6$ km³ and $27 \cdot 10^6$ km³ respectively.

Taking an ice density of $\rho = 0.92$ g/cm³, we express the masses of the northern and southern ice caps of the Earth in units of the Earth's mass $m = 0.597 \cdot 10^{28}$ g. For the two epochs considered, we have:

$$\begin{aligned} m_A^0 &= 0.54 \cdot 10^{-5} m, & m_A &= 0.42 \cdot 10^{-5} m, \\ m_G^0 &= 1.00 \cdot 10^{-5} m, & m_G &= 0.05 \cdot 10^{-5} m. \end{aligned} \quad (5)$$

To solve the problem of the ECM displacement, we must know not only the change of the ice sheets' masses, but also the change of the positions of their centers of masses. To determine these positions, we use the following simplest model of the ice caps and some additional simplified assumptions: (i) each of the caps is a thin spherical segment with homogeneous ice distribution (a similar model was considered by Whar et. al., 1993); (ii) the segment boundary is circular, and angular distance from segment center is characterized by angle α ; (iii) during the period (t_0 , t), centers of the ice caps had negligible displacements, and their positions correspond to the present-day positions of the ice sheets (86° 3' S, 112° 5' E for the southern cap and 73° 5' N, 47° 9' W for the northern cap); (iv) angular sizes of the northern and southern caps α are 40° and 30° (for epoch t_0), 10° and 20° (for present epoch t); (v) ice masses are characterized by homogenous distribution and by masses (5); (vi) processes of the melting and rise of the sea level are eustatic and uniform.

The distance between the cap center and geocenter is

$$r_\sigma = \frac{1}{2} R (1 - \cos \alpha_\sigma), \quad (6)$$

where R is the Earth's radius and α_σ is angular size of the cap. Displacement (6) is directed toward the center of the corresponding spherical segment occupied by the cap [see (ii)].

For the adopted model values from (iv), using formula (6), we found the values of the radial coordinates of the caps' centers of mass at epochs t_0 and t :

$$\begin{aligned} r_G^0 &= 5600 \text{ km}, & r_A^0 &= 5900 \text{ km}, \\ r_G &= 6300 \text{ km}, & r_A &= 6200 \text{ km}, \end{aligned} \quad (7)$$

Coordinates of the cap centers and values (7) completely determine the radii-vectors of the ice cap centers $\bar{r}_G^0, \bar{r}_A^0$ and $\bar{r}_G, \bar{r}_A$ at epochs t_0 and t , respectively.

Masses (5) and coordinates (7) allow us to estimate a change of the static moment of the ice masses. Change of the static moment of the ocean masses, grown during the period (t_0, t) at a mean rate of $\dot{z}_0 = 12.5$ mm/yr, in accordance with section 2, will be:

$$\bar{S}_0 = m \begin{pmatrix} -0.02929 \\ -0.02948 \\ -0.03700 \end{pmatrix} z_0,$$

where $z_0 = 125$ m.

Displacement vector $\bar{r}$ of the ECM during the period of time (t_0, t) , due to the considered redistribution of the ice-water masses is determined from the equation of conservation of the static moment of the Earth's masses:

$$m_A^0 \bar{r}_A^0 + m_G^0 \bar{r}_G = m_A \bar{r}_A + m_G \bar{r}_G + \bar{S}_0 + m \bar{r}. \quad (8)$$

Equation (8) allows us to find displacements of the ECM and corresponding mean rates in the period (t_0, t) for each of the processes considered and their full effect. We come to the following final conclusions.

1. Due to melting of the northern ice cap in the first 10,000 years after the maximum of the last glaciation, the ECM has moved by 53 meters southward in the direction of the geographic point $73^\circ.5$ S, $138^\circ.1$ E. The mean rate of this displacement was 5.3 mm/yr.
2. Due to melting of Antarctic ice in period (t_0, t) , the ECM has moved by 6.3 meters from its initial position northward in the direction $86^\circ.3$ N, $292^\circ.5$ E. The rate of this displacement was 0.63 mm/yr.
3. Due to ice transformation to oceanic masses and increasing of the sea level on 125 meters in period (t_0, t) , the ECM has moved by 7.0 meters in the direction $41^\circ.7$ S, $225^\circ.2$ E. The rate of this displacement was 0.70 mm/yr.
4. Under the action of all the above-mentioned mechanisms of transformation and redistribution of the ice-water masses of the Earth during the period of time (t_0, t) , the ECM has moved by 52 meters in the direction of the geographical point $72^\circ.1$ S, $157^\circ.7$ E. The mean rate of the displacement was 5.2 mm/yr.

These estimates show that during certain periods of the Earth's history, particularly in periods of fast and catastrophic changes of its dynamical structure, the effects of displacements of the ECM may be quite significant.

On the other hand, variations of the ECM position must lead to some dynamical effects in relative motions of the Earth's envelopes due to change of their positions with respect to the Earth's axis of rotation. In this connection, a further study of the ECM displacements at different timescales is a very important task.

The above estimates were obtained for the rigid model of the Earth crust. Visco-elastic properties of the crust and other accompanying redistributions of the Earth's masses will lead to some corrections of these displacements. These corrections can be studied separately using the well-known approach (Nakiboglu and Pointon, 1986; O'Connell, 1971; Wu and Peltier, 1984). Here we do not consider these effects, taking into account our crude model.

Periods of glaciations are cyclic. They are repeated every 100,000 years. It is known that sea level "serrately" changes in accordance with this process. The above-obtained results directly show that change of the direction of the glaciation process will reverse the direction of the ECM displacement. According to these simplified concepts and models, during a glacial period the ECM

tends to move northward, and after periods of maximum glaciation the ECM tends to move southward.

Displacements of the ECM lead to a change in the positions of the centers of masses of the mantle, fluid core, and rigid core with respect to the Earth's rotation axis. It means that in the relative motions of these structures there must be certain dynamic effects (variations of their relative rotations, etc.).

4. SUBDUCTION OF PLATES AND THE DRIFT OF THE EARTH'S CENTER OF MASSES

4.1. Variations of the coefficients of the first and second harmonics of the geopotential

Let us now investigate the effect of global tectonic motions on the displacement (drift) of the ECM, namely the influence of the motion of plates, their subduction and accumulation of masses of the submerging oceanic plates along the subduction zones. The role and contributions of other geodynamic processes to the ECM motion can be studied separately. The aim of this work is to estimate the parameters of the ECM drift at the modern geological epoch.

One of the main regularities, found by the method of seismic tomography, is the presence of excess masses along the subduction zones at depths of 350–550 km. The excess of masses in the subduction zones is caused by the relatively cool matter of the oceanic lithosphere, pushed under the volcanic arcs; this cool matter forces the hot mantle matter of the arcs upward (Hain and Zverev, 1991). The global structures, revealed in the mantle by the method of seismic tomography, are associated with the accumulation of the oceanic-plate blocs, submerging along the subduction zones. The ring of the regions with increased seismic velocities, surrounding the Pacific Ocean, is due to subduction and accumulation of masses at depths of about 1000 km. It is noted that this process has been taking place during the last 200 millions of years (Dziewonski and Ekstrem, 1996).

The process of formation of inhomogeneities is dynamic; it is lasting at geological time intervals. For this reason alone, the excess masses cannot get a complete isostatic compensation, especially under the conditions, where the rotation axis is changing its position in the Earth's body. All the nonspherical, unbalanced Earth's envelopes interact in a complex manner; this interaction inevitably results in their relative displacements. The excess masses along the subduction zones have been accumulating there at a certain rate during millions of years. Certainly, this must have a reflection in variations of the geopotential coefficients, Earth's rotation, and ECM position.

We proposed two methods of determination of the components of the Earth's tensor of inertia, caused by the mechanism of subduction and accumulation of masses. One of the mechanisms is basing on the analytical description of "the effect of overlap of plates" along the subduction zones; it is based on the kinematic theory of the absolute motion of plates (Barkin, 1995a, 1996). The other method – a more direct one – uses the procedure of analysis of mass inflow rate over all the subduction zones and determination of the corresponding variations of the components of the tensor of inertia (Barkin, 1996). This procedure is reduced to calculation of volume integrals over the subduction zones. In this case, we use the well-known data on the thickness of the submerging lithosphere ($H = 80$ km), its mean density ($\rho = 3.3$ g/cm³) as well as the parameters of the kinematic theory of the relative motion of plates (Ushakov and Galushkin, 1978).

We will call the fraction of the accumulated masses in the total masses, submerging in the subduction zones, the coefficient of the mass accumulation intensity i_a . We estimated this parameter, in particular, by an analysis of the parameters of the model of the nonuniform, nonspherical Earth's envelopes and envelopes of its inhomogeneities (Barkin, 1997); we also used data on the features of the global tectonic process during the last 43 million years. As a result, we established that a fraction $i_a = 1/3$ of the total mass of oceanic plates, inflowing to the subduction zones, is subject to accumulation.

Variations of the coefficients of the first and second geopotential harmonics, calculated with the above rate of accumulation of the oceanic-plate masses, are:

$$\begin{aligned}
 \dot{C}_{10} &= 0.336 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{C}_{11} &= -1.257 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{S}_{11} &= 0.278 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{J}_2 &= 0.648 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{C}_{21} &= -0.290 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{S}_{21} &= 0.433 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{C}_{22} &= -0.174 \cdot 10^{-9} \text{ century}^{-1}, \\
 \dot{S}_{22} &= -0.321 \cdot 10^{-9} \text{ century}^{-1},
 \end{aligned} \tag{9}$$

4.2. Paleomigration of the Earth's pole

Dynamic investigations show that secular motion of the Earth's rotation axis pole P_ω is due to redistribution of masses in the deformable Earth, which lead to variations of the Earth's products of inertia or of the corresponding geopotential coefficients C_{21} , S_{21} . We will use the results of an analytical description of secular effects in the rotational motion of a celestial body with a deformable outer envelope (Barkin, 1996). The motion of the pole with velocities (1) is referred to the main central axes of inertia of the body for the given epoch $Cx_0y_0z_0$. The vector of angular velocity $\vec{\omega}$ describes the rotation of precisely this system of coordinates. Variations $\dot{C}_{21}$, $\dot{S}_{21}$ are determined with respect to the system of coordinates $Cx_0y_0z_0$, too.

The main components of the pole drift velocity P_ω in coordinate axes Cx_0 , Cy_0 are given by the following simple formulae:

$$\dot{p} = \omega \left(\frac{\omega}{\Omega} + 1 \right) \frac{\dot{C}_{21}}{I}, \quad \dot{q} = \omega \left(\frac{\omega}{\Omega} + 1 \right) \frac{\dot{S}_{21}}{I}.$$

Here ω and Ω are the frequencies of the unperturbed Chandler motion of the body, $\omega + \Omega$ is the rate of the Earth's diurnal rotation, $I = \frac{C}{mR^2}$ is the dimensionless moment of inertia (C , m and R are the polar moment of inertia, mass, and mean radius of the deformable body, respectively), $\dot{C}_{21}$, $\dot{S}_{21}$ are secular variations of geopotential coefficients C_{21} , S_{21} .

Thus, owing to a slow rebuilding of the body's dynamic structure, the pole of the rotation axis P_ω is moving at angular velocity v_ω along meridian λ_ω , where

$$v_\omega = \left(\frac{\omega}{\Omega} + 1 \right) \frac{\sqrt{\dot{C}_{21}^2 + \dot{S}_{21}^2}}{I}, \quad \lambda_\omega = \arctan \left(\frac{\dot{C}_{21}}{\dot{S}_{21}} \right). \tag{10}$$

The Earth's dynamic structure is close to that of an axisymmetric body; therefore, formulae (10) conserve their form if we use the Greenwich system of coordinates as the main one. In this case, λ_ω is the Greenwich longitude, and variations $\dot{C}_{21}$, $\dot{S}_{21}$ are also defined in the Greenwich system of coordinates.

For the values of $\dot{C}_{21}$, $\dot{S}_{21}$ from (9), we find with (10) that the pole of the Earth's rotation axis is moving at velocity $v_\omega = 0^\circ.40 \text{ Myear}^{-1}$ along the meridian $\lambda_\omega = 56^\circ.2 \text{ W}$. The parameters found are in a good agreement with their "observed" values for the Earth's pole, obtained by the paleomagnetic methods (Sabadini and Yuen, 1989):

$$v_\omega = 0^\circ.56 \text{ Myear}^{-1}, \quad \lambda_\omega = 40^\circ \text{ W}.$$

Thus, the main cause of the Earth's pole paleomigration is the global tectonic process and the accompanying geodynamic processes of subduction and accumulation of masses of the oceanic plates. For the value we have found for the coefficient of the mass accumulation rate, the pole paleomigration at the present epoch gets a full explanation, in both magnitude and direction.

Richards and Hager (1984), Hager et al. (1985) developed another approach to the explanation of the drift of the Earth's axis pole; in these works, the clue role belongs to the mechanism of mantle convection, taking into account the presence of heterogeneities in the mantle, peculiarities of plate geometry and motions, their subduction, etc. The model, proposed in this work, is simpler and, seemingly, more feasible from the mechanical point of view. It has allowed us to estimate secular variations of the geopotential coefficients (the first and second harmonics) and, in particular, to reveal a new fundamental phenomenon in geodynamics – secular drift of the Earth's center of masses.

4.3. Variation of J_2

The value of variations of coefficient J_2 of the geopotential, obtained on the basis of laser observations of the Earth's satellites during the last 20 years, is estimated as

$$\dot{J}_2 = (-2.7 \pm 0.4) \cdot 10^{-9} \text{ cy}^{-1} \text{ (Yoder et. al., 1983; Cheng et. al., 1997).}$$

On the other hand, interpretation of variation $\dot{J}_2$ due to postglacial situation yields a greater value $\dot{J}_2 = (-3.2 \pm 0.3) \cdot 10^{-9} \text{ cy}^{-1}$ (Yoder, 1998).

Thus, the “observed” discrepancy $\Delta \dot{J}_2 = 0.5 \cdot 10^{-9} \text{ cy}^{-1}$ can be explained by this additional “tectonic” variation from (9) $\dot{J}_2 = 0.65 \cdot 10^{-9} \text{ cy}^{-1}$.

4.4. Secular drift of the Earth center of masses

For the above-mentioned mechanism of change of the Earth's dynamical structure, the variations of the first harmonic coefficients of the geopotential were determined. The corresponding components of the velocity of the secular drift of the ECM are:

$$\dot{x}_C = -0.801 \text{ cm/cy}, \quad \dot{y}_C = 0.177 \text{ cm/cy}, \quad \dot{z}_C = 0.214 \text{ cm/cy}.$$

Due to formation of heterogeneities and excess masses in the regions of the subduction zones, the ECM moves about its position in the given epoch at a velocity of 0.47 cm/cy in the direction of the geographic point 14° 6' N, 167° 6' E. This direction correlates with the direction from geocenter to magnetic center of the Earth (15° 1' N, 150° E) and with the direction of vector of the momentum of the lithosphere plates' motion according to the NNR-NUVEL1 theory (Barkin, 1996). Displacement of the ECM corresponds to relative displacement of the centers of mass of the fluid core and mantle. It is a significant evidence that the nature of the eccentricity of the Earth's magnetic field is connected with the excentricity of the center of masses of the fluid core w.r.t. the Earth's axis of rotation.

The secular effects in the ECM motion are probably too small to be detected by current satellite observations (Montag et. al., 1995). However, some other secular or long-period variations of the ECM position can take place, for example, due to displacements and motion of the rigid core (Barkin, 1997). In this connection, experimental determination of the parameters of the ECM drift is an important problem.

5. CONCLUSION

The estimates obtained of the ECM secular motion parameters due to redistribution of the ice-water masses in the present and postglacial epochs are preliminary. They were obtained for the simplest models of the transformation and redistribution of the masses. We have used these models because of big errors in the parameter values characterizing these processes. In future we

will consider the role of the elastic and visco-elastic properties of the Earth, following the known approaches (Wu and Peltier, 1984; Nakiboglu and Poinçon, 1986; O'Connell, 1971, and others).

The global tectonic process (subduction, mass accumulation processes and others) gives a significant contribution to the observed Earth's pole drift (practically, this process explains paleomigration of the pole w.r.t. mantle reference system), and to variation $\dot{J}_2$ (it explains the "observed" discrepancy $\Delta\dot{J}_2$). This global process also determines the slow drift of the ECM. The last effect reflects the eccentricity of the center-of-mass positions of the fluid core, mantle, and other Earth's envelopes. Displacements of the centers of masses of these envelopes, caused by Earth's mass redistribution and by mutual interactions, manifest themselves at geological time intervals and have an important significance for the geodynamic history and evolution of the Earth..

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Synthesis of submitted geocenter time series

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This paper is devoted to the analysis of all the geocenter time series submitted to GEOC web site, the official IERS geocenter campaign web site. The data are analyzed through a regression analysis, in order to determine an annual signal and a semi-annual signal (Eq. 1). The results are presented in terms of amplitude and phase, the latter measured with respect to the 1st of January.

$$s(t) \cong A_0 + A'_0 t + A_1 \cos(\omega_1 t + \varphi_1) + A_{1/2} \cos(\omega_{1/2} t + \varphi_{1/2}) \quad (1)$$

A constant term, as well as a trend are also estimated, in order to express the whole time series in a common reference frame. When the standard deviations were available, they have been used as weights for the regression ; if not, the weights were chosen to be equal.

The uncertainties given in the following tables were computed with the use of a χ^2 term of normalization. It must be emphasized that this χ^2 corresponds to the quality of the fit of model (1). Therefore, if the model (1) is not appropriate, one should not conclude from large uncertainties a poor quality of the data.

1 Submitted data

1.1 SLR

5 SLR geocenter time series have been submitted. The summary of these time series is given in Tab. 1.

Center	Name of the series	Span (in dec. years)	Sample (in days)	Transmitted by
CSR	CSRL-Topex	1992.7 - 1997.4	10	M. Cheng
CSR	CSRL-Lag	1992.8 - 1997.0	14	R. Eanes
GSFC	GSFCL	1993.0 - 1997.0	14	E. Pavlis
ASI	ASI1	1993.0 - 1997.0	14	P. Rutigliano G. Luceri
ASI	ASI2	1993.0 - 1997.0	14	P. Rutigliano G. Luceri

Table 1: Submitted SLR time series

1.2 DORIS

3 DORIS geocenter time series have been submitted. The summary of these time series is given in Tab. 2.

Center	Name of the series	Span (in dec. years)	Sample (in days)	Transmitted by
IGN	IGND-M	1994.0 - 1997.5	30	P. Willis P. Sillard
IGN	IGND-W	1994.2 - 1996.7	7	P. Willis
GRGS	GRGSD	1993.1 - 1996.9	30	F. Bouillé

Table 2: Submitted DORIS time series

1.3 GPS

3 GPS geocenter time series have been submitted. The summary of these time series is given in Tab. 3.

Center	Name of the series	Span (in dec. years)	Sample (in days)	Transmitted by	
SIO	SIOG	1992.6 - 1997.5	1	T. Herring	
EMR	EMTG	1996.2-1996.7	7	Y. Kouba	no computation
JPLgn	JPLGN	1996.8 - 1998.7	7	Y. Kouba	
MITgn	MITGN	1996.8 - 1998.7	7	Y. Kouba	
NCLgn	NCLGN	1996.8 - 1998.7	7	Y. Kouba	
GFZ	GFZG	1995.4 - 1997.0	1	S. Zhu	
JPL	JPLG	1991.0 - 1997.2	1	M. Heflin	
IGN/JPL	IJG	1995.6 - 1997.2	1	P. Sillard M. Heflin	

Table 3: Submitted GPS time series

1.4 Combined

Center	Name of the series	Span (in dec. years)	Sample (in days)	Transmitted by
IGN	IGNGD	1995.6 - 1997.2	30	P. Sillard

Table 4: Submitted Combined time series

2 Results

2.1 SLR

The values obtained by Cheng, from the CSRL-Tpex time series are :

	Sa mm/deg	Ssa mm/deg
x	2.09/39.5	0.25/64.4
y	4.67/ 9.7	0.52/76.4
z	1.20/58.8	0.15/295.5

These values are quite close to ones which were computed in the present studies, except from the fact that the phase is shifted with a value of $\pi/2$. This is explained by a difference in the model (1) which must be written $\sin(\omega t + \varphi)$ instead of $\cos(\omega t + \varphi)$.

Time series	A_1 <i>mm</i>	ϕ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\phi_{1/2}$ <i>deg</i>
<i>CSRL – Topex</i>	2.1	-53.2	0.24	148.
	± 0.81	$\pm 11.$	± 0.81	$\pm 97.$
<i>CSRL – Lag</i>	2.1	-58.8	1.2	77.2
	± 0.64	± 8.9	± 0.64	$\pm 16.$
<i>GSFCL</i>	0.5	-47.4	0.72	108.
	± 0.72	$\pm 41.$	± 0.73	$\pm 29.$
<i>ASI1</i>	0.54	67.1	0.76	-168.
	± 1.1	$\pm 61.$	± 1.1	$\pm 42.$
<i>ASI2</i>	1.4	0.183	2.	48.1
	± 1.4	$\pm 27.$	± 1.4	$\pm 20.$

Table 5: SLR annual and semi-annual components in X

Time series	A_1 <i>mm</i>	ϕ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\phi_{1/2}$ <i>deg</i>
<i>CSRL – Topex</i>	4.7	97.3	0.52	162.
	± 0.76	± 4.9	± 0.77	$\pm 43.$
<i>CSRL – Lag</i>	3.2	59.5	0.68	111.
	± 0.73	± 6.8	± 0.74	$\pm 31.$
<i>GSFCL</i>	1.	52.2	0.26	-178.
	± 0.85	$\pm 24.$	± 0.85	$\pm 95.$
<i>ASI1</i>	3.3	-119.	1.4	-114.
	± 1.2	$\pm 11.$	± 1.2	$\pm 25.$
<i>ASI2</i>	0.78	-177.	1.6	-49.
	± 1.4	$\pm 47.$	± 1.3	$\pm 24.$

Table 6: SLR annual and semi-annual components in Y

Time series	A_1 <i>mm</i>	ϕ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\phi_{1/2}$ <i>deg</i>
<i>CSRL – Topex</i>	1.2	-33.7	0.16	19.3
	± 0.35	± 8.2	± 0.35	$\pm 64.$
<i>CSRL – Lag</i>	2.9	-44.1	0.37	-64.2
	± 1.6	$\pm 16.$	± 1.6	$\pm 130.$
<i>GSFCL</i>	3.2	129.	2.1	92.3
	$\pm 3.$	$\pm 27.$	$\pm 3.$	$\pm 40.$
<i>ASI1</i>	3.6	160.	2.4	152.
	± 3.7	$\pm 28.$	± 3.7	$\pm 42.$
<i>ASI2</i>	4.	-134.	4.3	87.4
	± 3.7	$\pm 26.$	± 3.7	$\pm 24.$

Table 7: SLR annual and semi-annual components in Z

2.2 DORIS

Time series	A_1 <i>mm</i>	φ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg</i>
<i>IGND - M</i>	5.6	79.7	4.2	-160.
	$\pm 5.$	$\pm 25.$	± 4.8	$\pm 34.$
<i>IGND - W</i>	4.8	6.71	3.2	-167.
	± 2.5	$\pm 15.$	± 2.4	$\pm 23.$
<i>GRGSD</i>	3.2	-153.	1.5	117.
	± 0.99	± 8.7	± 0.98	$\pm 18.$

Table 8: DORIS annual and semi-annual components in X

Time series	A_1 <i>mm</i>	φ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg</i>
<i>IGND - M</i>	9.3	-39.7	1.9	-123.
	± 2.2	± 6.7	± 2.2	$\pm 32.$
<i>IGND - W</i>	11.	-45.6	2.7	-91.3
	± 2.6	± 6.6	± 2.6	$\pm 27.$
<i>GRGSD</i>	4.2	60.4	0.88	-76.6
	± 1.3	± 8.9	± 1.3	$\pm 42.$

Table 9: DORIS annual and semi-annual components in Y

Time series	A_1 <i>mm</i>	φ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg</i>
<i>IGND - M</i>	19.	168.	11.	-63.4
	± 5.1	± 8.4	± 5.4	$\pm 14.$
<i>IGND - W</i>	20.	164.	36.	-138.
	$\pm 12.$	$\pm 16.$	$\pm 11.$	± 9.2
<i>GRGSD</i>	5.6	50.6	0.94	-48.2
	± 5.2	$\pm 27.$	± 5.2	$\pm 160.$

Table 10: DORIS annual and semi-annual components in Z

2.3 GPS

The values obtained by Zhu comparable to the series GFZG are the following ones :

	X	Y	Z
amplitude (1y period)	4.3mm	9.1mm	6.8mm
phase (degree)	-3.9	24.4	.6
amplitude (1/2y period)	2.7mm	4.7mm	5.2mm
phase (degree)	4.4	40.7	-23.2

For annual term, the values are nearly coherent but for the semi annual term, there is a significant difference. An explanation could be probably found with the applied model. Is the regression of annual and semi-annual term carried out simultaneously?

Time series	A_1 <i>mm</i>	ϕ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\phi_{1/2}$ <i>deg</i>
<i>SIOG</i>	1.4	179.	1.9	-42.2
	± 2.1	$\pm 43.$	± 2.1	$\pm 32.$
<i>JPLGN</i>	3.6	142.	0.99	-20.7
	± 1.2	$\pm 10.$	± 1.2	$\pm 35.$
<i>MITGN</i>	2.6	118.	1.7	-27.9
	± 1.3	$\pm 14.$	± 1.3	$\pm 21.$
<i>NCLGN</i>	3.9	147.	1.	-27.7
	± 1.2	± 8.6	± 1.2	$\pm 31.$
<i>GFZG</i>	4.	-76.9	1.7	167.
	$\pm 2.$	$\pm 13.$	± 1.9	$\pm 33.$
<i>JPLG</i>	5.8	101.	3.	-68.1
	± 1.6	± 7.2	± 1.5	$\pm 15.$
<i>IJG</i>	5.3	-15.0	7.3	-98.3
	± 4.8	$\pm 23.$	± 4.1	$\pm 19.$

Table 11: GPS annual and semi-annual components in X

Time series	A_1 <i>mm</i>	ϕ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\phi_{1/2}$ <i>deg</i>
<i>SIOG</i>	0.96	44.8	2.1	-178.
	± 1.9	$\pm 57.$	± 1.9	$\pm 26.$
<i>JPLGN</i>	12.	-70.6	5.6	32.6
	$\pm 3.$	± 7.1	± 2.9	$\pm 15.$
<i>MITGN</i>	5.3	-132.	1.6	43.3
	± 2.2	$\pm 12.$	± 2.2	$\pm 40.$
<i>NCLGN</i>	7.6	-78.8	5.3	47.7
	± 2.8	± 9.7	± 2.6	$\pm 14.$
<i>GFZG</i>	9.2	114.	7.3	-68.
	± 2.2	± 6.6	± 2.2	± 8.3
<i>JPLG</i>	9.5	157.	5.3	-37.9
	± 1.5	± 4.7	± 1.5	± 8.1
<i>IJG</i>	8.6	174	1.5	120.
	± 2.5	± 7.2	± 2.2	$\pm 46.$

Table 12: GPS annual and semi-annual components in Y

Time series	A_1 <i>mm</i>	ϕ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\phi_{1/2}$ <i>deg</i>
<i>SIOG</i>	7.4	-89.1	15.	114.
	± 4.8	$\pm 19.$	± 4.8	± 9.3
<i>JPLGN</i>	17.	11.4	9.	13.4
	± 4.1	± 6.9	± 4.1	$\pm 13.$
<i>MITGN</i>	19.	4.71	6.1	3.37
	± 3.5	± 5.6	± 3.7	$\pm 17.$
<i>NCLGN</i>	16.	4.79	8.6	-0.406
	± 3.5	± 6.6	± 3.7	$\pm 12.$
<i>GFZG</i>	6.7	118.	5.1	-5.36
	± 2.3	± 9.2	± 2.1	$\pm 12.$
<i>JPLG</i>	42.	15.	8.2	0.655
	± 4.1	$\pm 3.$	± 4.2	$\pm 15.$
<i>IJG</i>	19.	-32.0	17.	-30.2
	± 6.7	± 9.9	± 7.3	$\pm 11.$

Table 13: GPS annual and semi-annual components in Z

2.4 Combination

Time series	A_1 <i>mm</i>	φ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg</i>
<i>IGNGD</i>	2.5 ± 5.7	38.9 $\pm 64.$	4.6 ± 5.2	102. $\pm 36.$

Table 14: GPS and DORIS combined annual and semi-annual components in X

Time series	A_1 <i>mm</i>	φ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg</i>
<i>IGNGD</i>	2.4 ± 3.2	-54. $\pm 40.$	2.9 $\pm 3.$	-81.3 $\pm 33.$

Table 15: GPS and DORIS combined annual and semi-annual components in Y

Time series	A_1 <i>mm</i>	φ_1 <i>deg</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg</i>
<i>IGNGD</i>	12. $\pm 10.$	41.7 $\pm 26.$	14. ± 9.7	-62.7 $\pm 22.$

Table 16: GPS and DORIS combined annual and semi-annual components in Z

3 Conclusion and proposed resolution

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 physical signal. Nevertheless, research in this field should be carried on. This could be also the occasion to really check the compatibility of various models used in data reduction, especially the ones which may have a non-isotropic seasonal signature. Understanding the sensitivity of Space Geodesy to geocenter variations should be a major goal for both the Global Geophysical Fluids sub-bureau of IERS and the pilot project on ITRS time series.

GEOCENTER VARIATIONS DERIVED FROM 5 YEARS OF DATA OF THE DORIS SPACE SYSTEM. COMPARISON WITH SURFACE LOADING DATA

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ABSTRACT – The Earth centre of mass plays a crucial role as the origin of the terrestrial reference system. Because of surface mass redistribution, its position varies with respect to the centre of figure, the geocenter. Space techniques are now precise enough to allow geocenter motion determination. Here we present estimates of geocenter coordinate time series over five complete years (1993-1997) from DORIS data on SPOT2, SPOT3 and TOPEX/POSEIDON. Amplitude and phase of the DORIS-derived annual cycle for each geocenter coordinate have been compared to surface mass redistribution at the Earth surface estimated from different geophysical sources.

INTRODUCTION

The DORIS space system has been developed in France in the early 90s to become the nominal tracking system of the TOPEX/POSEIDON altimeter satellite launched in 1992. Prior to TOPEX/POSEIDON, DORIS had been placed on board the remote sensing satellite SPOT2 for a test mission of 6 months. SPOT2 was launched in January 1990. Nearly 8 years later, the DORIS instrument on board SPOT2 is still operationally functioning. DORIS was also onboard the SPOT3 satellite which worked from September 1993 until November 1996. The Groupe de Recherche de Géodésie Spatiale (GRGS) is currently involved in DORIS data analysis on the three satellites SPOT2, SPOT3 and TOPEX/POSEIDON for the determination of 3-D absolute coordinates and velocities of the permanent DORIS network station. The analysis is based on the GRGS's GINS/DYNAMO software developed for precise orbitography and geopotential modeling. There are now 52 permanent DORIS stations in operation throughout the world. Some of them are collocated with GPS, VLBI and SLR stations. Recently, we have attempted to determine the motion of the geocenter. In fact, analyses of satellite tracking data have provided persuasive evidence that the reference frame formed by the tracking stations attached to the Earth's crust moves relative to the Earth's centre of mass. This translation motion, when viewed from a crust-fixed reference frame, is known as « geocenter motion » and is caused by the mass redistribution of the fluid envelopes, primarily the atmosphere, oceans and continental ground waters. Here, we present time series of the three geocenter components derived from DORIS as well as a comparison with the contributions estimated from variations in atmospheric surface pressure, ocean, land water storage and snow/ice cover.

GEOCENTER VARIATIONS FROM DORIS

The analysis of DORIS data on SPOT2, SPOT3 and TOPEX/POSEIDON has been performed over 5 complete years (January 1993 to December 1997). The approach is a geometrical one, consisting of computing the translation parameters of an Helmert transformation between successive monthly coordinate solutions of the global DORIS network and a multi-year reference solution. The DORIS station coordinates define the reference system and its centre is the centre of figure whose position from one month to

another varies. These variations measured relative to an empirically defined reference position, are interpreted as the geocenter motions.

To determine the geocenter coordinates, a reference solution over the 5 years has been computed as well as monthly coordinate solutions. The method of analysis used to obtain the coordinate solutions is detailed in Cretaux et al. (1998). Differences between each monthly solution and the 5-year solution have been minimized through a least squares process by adjusting classical translation, rotation and a scale factor parameters. Time variations of the translation parameters are interpreted as the geocenter motion during 1993-1997 relative to a mean position over that period. Fig.1 shows the time evolution of the 3 geocenter coordinates (units are in millimeter) with an annual cycle adjusted for each component. The X and Y coordinates show a clear seasonal signal. Annual amplitudes are 4.59 mm, 4.06 mm and 3.93 mm for X, Y and Z components respectively.

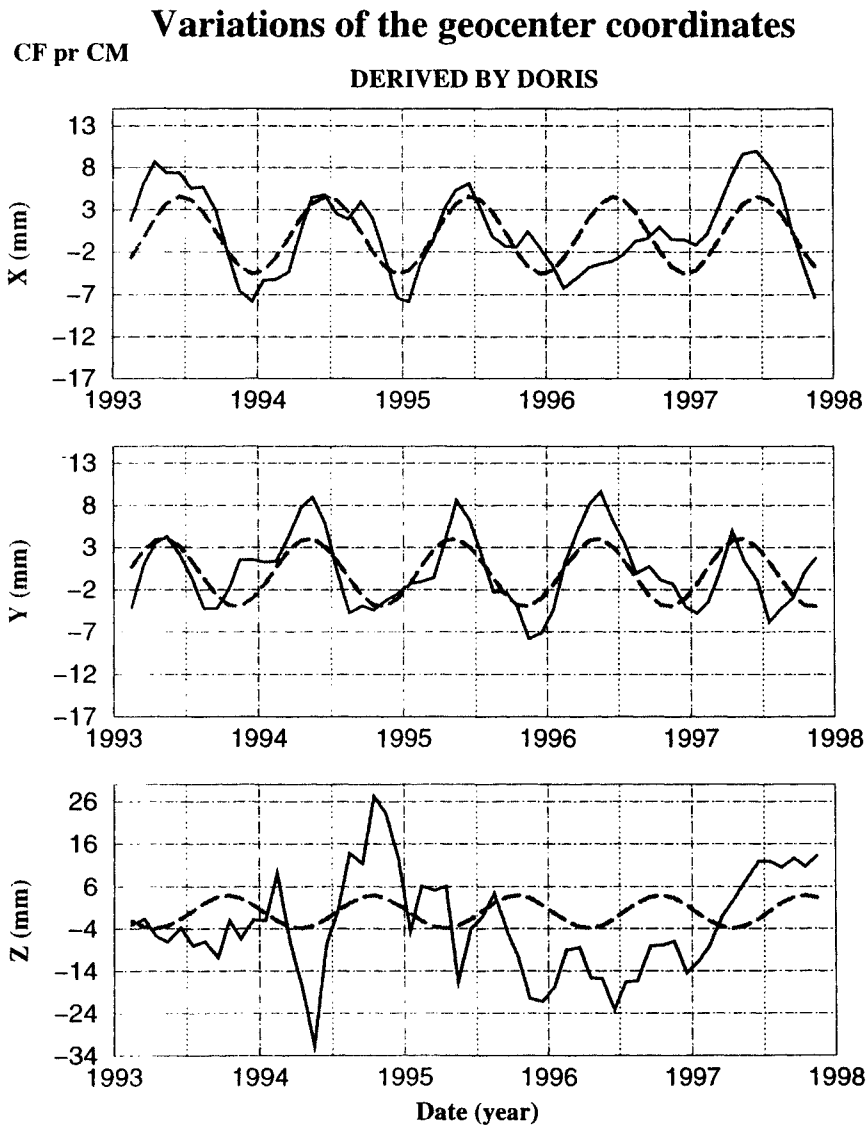


Fig.1 : Geocenter motion determined by DORIS over 1993-1997. The adjusted annual harmonic is superimposed for each coordinate.

The DORIS–derived geocenter variations have been compared to other determinations based on different methods or different space systems (e.g., SLR or GPS). We note a good agreement with recent laser determinations from the Texas group, in particular for the Y component. The agreement is less good for X and rather bad for Z. We note that there is still large discrepancies between the various solutions, an indication that more work is needed to get reliable geocenter coordinates.

GEOCENTER VARIATIONS FROM SURFACE MASS LOAD

Global mass redistribution alters the Earth rotation, produces temporal variations of the gravitational field, and also shifts the position of geocenter. The estimated geocenter variations from surface mass redistribution can be directly compared to the DORIS-derived geocenter variations. Below are discussed geocenter variations arising from surface loads such as atmospheric pressure, ocean and surface ground waters.

Atmospheric loading contribution

Atmospheric mass redistribution is classically deduced from atmospheric surface pressure variations. We used ECMWF gridded surface pressure fields given every 6 hours for the period 1988-1996. Monthly averaged values have been first computed and harmonic expansion has been performed for each monthly grid. Over the oceans, an inverted barometer response has been assumed. The degree 1 coefficients of the spherical harmonic expansion of surface pressure have been transformed into degree 1 coefficients of the gravitational potential using the well known relation :

$$\begin{pmatrix} \Delta C_{nm} \\ \Delta S_{nm} \end{pmatrix} = \frac{(1 + k'_n) R^2}{(2n + 1) M} \int_S \Delta q(\varphi, \lambda) \begin{pmatrix} \cos \\ \sin \end{pmatrix} (m\lambda) P_{nm}(\sin \varphi) dS \quad (1)$$

with $\Delta q = \frac{\Delta p}{g}$

Δp : Surface pressure variation

R, M : Radius and mass of the Earth

g : Mean surface gravity

k'_n is the load Love number of degree n.

The degree 1 terms have been further expressed in terms of geocenter coordinates X, Y, Z, as written below :

$$\begin{aligned} X &= RC_{11} \\ Y &= R S_{11} \\ Z &= RC_{10} \end{aligned} \quad (2)$$

The atmospheric contribution computed in this study agrees quite well with that of Dong et al. (1997) based on another data set.

Ocean loading contribution

The ocean contribution to the geocenter variations has two components : (1) water mass redistribution due to regional change of the ocean circulation and (2) global sea level change. For the first contribution, we used geocenter variations estimated by Dong (see Dong et al., 1997) who based their computations on two ocean general circulation models. (ISO and MOM). The ocean has the biggest contribution in the x component with 1.05 mm for the annual term. The latter contribution is small but easy to estimate. We computed the seasonal change in the global mean sea level using altimeter data of the TOPEX/POSEIDON satellite (see Minster et al., 1998 for details). The observed mean sea level has been corrected for steric effects and the contribution to the geocenter computed as explained in Chao and O'Connor (1988). At the annual frequency this effect is quite small, less than 0.2 mm in amplitude.

Continental waters

Continental water storage varies over the year in response to annual changes in precipitation, evapotranspiration, snowcover and river runoff. We used the continental water climatology of Willmott and co workers (Willmott et al., 1985), distributed by the National Centers for Environmental Predictions (NCEP). This climatology provides monthly grids of soil moisture and snow load. These gridded data sets have been developed into spherical harmonics. The degree 1 coefficients have been transformed into geopotential coefficients and further expressed in terms of geocenter coordinates as explained above for the atmospheric contribution. For snow cover participation in geocenter motion , we have also estimated a geocenter motion with snow cover data from The International Satellite Land Surface Climatology Project (ISLSCP). Our results can be compared with those obtained from Willmott climatology with a difference in amplitude for the z component. This could be explained by a lack of snow cover data in Willmott climatology in some areas like Greenland, North of China and Antarctica. Whereas, the snow accumulation in these regions should influence a geocenter motion in the North-South direction.

COMPARISON BETWEEN DORIS-DERIVED AND SURFACE LOAD DERIVED GEOCENTER VARIATIONS

The sum of surface mass load contributions which induce geocenter variations can be compared in amplitude in phase with the DORIS-derived geocenter variations. Fig. 2 presents a comparison the DORIS-derived geocenter variations and the geophysical estimates. For the latter we have considered the atmosphere and continental waters as explained above. We also added the ocean contribution given in Dong et al. (1997), due to ocean circulation changes and in addition our estimation of geocenter variations from sea level change. Each geophysical contribution as well as their sum are shown in Fig.2 superimposed on the DORIS-derived geocenter coordinates. For Y and Z, the sum of the geophysical effects agree reasonably well with the observed variations. The snow contribution accounts for almost all observed signal in Z. For the X component, the total geophysical signal appears rather different from Doris estimation and the reason is unclear. It is unlikely that some missing signal would be able to explain such a difference. Further investigation is needed to understand this discrepancy. A comparison is also made with geocenter motion prediction made by Dong et al. (1997). Their results coincide rather well with geocenter variations derived with Doris data. Our geophysical prediction is not finished yet because soil moisture data which have been used from Willmott climatology are not optimal. Anyway, this good agreement with geophysical predictions in geocenter motion obtained by Dong shows that Doris results are satisfactory.

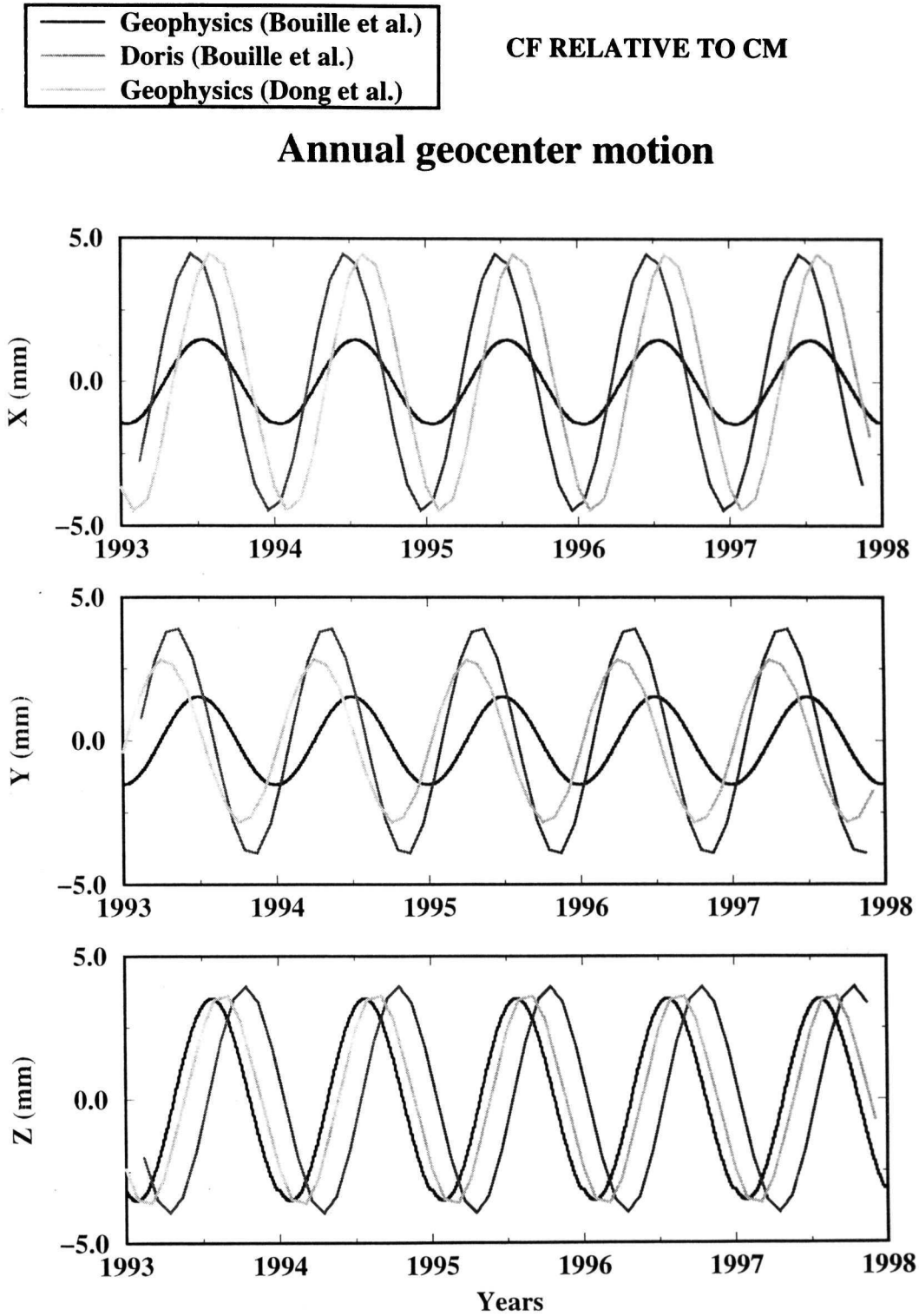


Fig.2: DORIS-derived geocenter coordinates and sum of the geophysical effects. A comparison is also made with geocenter motion predicted by Dong et al. from other geophysical data.

CONCLUSION

Owing to its global and well distributed station network, the DORIS system is quite suitable for measuring the geocenter motion. As for other space-derived solutions, the precision of the geocenter coordinates will increase as the time series lengthen.

In March 1998, another DORIS receiver has been placed in orbit, on the SPOT4 satellite. Early 2000, JASON 1 and ENVISAT will carry second generation DORIS receivers with lower instrumental noise. Thus we can reasonably hope improving the geocenter determination. Moreover, as now done for space-derived tectonic motions, combined solutions obtained from different space techniques will be computed. In addition to providing constraints on the still poorly known hydrological contribution at the annual frequency, measurements of interannual variations of the geocenter may be of great interest for global sea level changes derived by satellite altimetry since in this case measured sea surface height is referred in principle to the centre of mass.

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MASS VARIATIONS IN THE EARTH SYSTEM AND GEOCENTER MOTIONS

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ABSTRACT:

Mass redistributions within the Earth system, especially in its geophysical fluid envelope, the atmosphere, ocean, and continental water produce observable changes in geocenter motion, which is currently detectable from space geodetic techniques. We investigate mass variations in the atmosphere and continental water cycle and their potential contributions to geocenter motion using surface pressure, soil moisture, and snow accumulation from the NCEP/NCAR Climate Data Assimilation System I. In addition, sea surface anomalies determined by the TOPEX/POSEIDON altimeter are used to investigate geocenter variations resulting from ocean mass redistribution. A steric correction to sea surface height is calculated using the objectively analyzed temperature fields in the World Ocean Atlas 1994. A comparison with observed geocenter variations derived from Lageos 1 and 2 SLR data indicates that the atmosphere, oceans, and continental hydrological cycle all provide significant contributions at different frequencies and to different components. Geocenter variations estimated in this paper are in reasonably good agreement with the results given by *Dong et al.* [1997] for atmospheric and oceanic contributions, except for the estimates of continental hydrological contributions.

1. INTRODUCTION

The geocenter is defined as the mass center of the Earth system, including the solid earth, oceans, and atmosphere. Space geodetic techniques, such as Satellite Laser Ranging (SLR) and the Global Positioning System (GPS), have demonstrated that the geocenter moves a few mm to cm relative to the International Terrestrial Reference Frame (ITRF) over time scales ranging from diurnal to interannual [Watkins and Eanes, 1997]. The ITRF is defined by geodetic stations fixed to the earth's crust, and geocenter variations relative to the ITRF directly affect estimates of earth orientation, satellite orbital motion, low degree gravitational field variations, and all space geodetic measurements which use the ITRF as a reference system.

Observed geocenter variations are produced by mass redistribution within the Earth system, especially surface mass load changes associated with the atmosphere, oceans, and the continental hydrological cycle. *Dong et al.* [1997] estimated the geocenter variations caused by atmospheric pressure variations, ocean bottom pressure, and land water storage fluctuations using the European Center for Medium-range Weather Forecasts (ECMWF) atmospheric model, two ocean general circulation models (MOM and ISO), and a continental water storage data set compiled by *Lei and Gao* [1992]. They concluded that the amplitudes of geocenter variations introduced by geophysical fluids (air and water) were less than 1 cm, about the same magnitude as the observed geocenter motions [Dong et al., 1997].

In this study, we use different models of the atmosphere, continental hydrological cycle, and oceans to study mass redistribution in these three major components of the Earth system, and estimate the associated geocenter variations. Estimated geocenter variations are compared with observations from Lageos 1/2 SLR data, and with the results given by *Dong et al.* [1997].

According to the definition of geocenter (the mass center of the earth system), the geocenter vector ($\vec{R}_{cm}$) is defined from the ITRF origin to the mass center of the earth system. Mass redistribution within the earth system will change $\vec{R}_{cm}$. In spherical coordinates, mass load variations on a rigid earth affect $\vec{R}_{cm}$,

$$\vec{R}_{cm}(t) = \frac{1}{M_e} \int \vec{R} \cdot L(\phi, \lambda, t) \cdot ds \quad (1)$$

in which, ϕ is latitude, λ is east longitude, M_e is mass of the planet Earth, $L(\phi, \lambda, t)$ is mass load changes at the surface position $\vec{R}(\phi, \lambda)$ and time t , and $ds = R_e^2 \cdot \cos\phi \cdot d\phi \cdot d\lambda$ is surface area associated with mass load variation $L(\phi, \lambda)$, and R_e is the mean radius of the earth. $d\phi$ and $d\lambda$ are grid intervals. In Cartesian coordinates with a gridded surface mass load scheme, the three components (X, Y, Z) of geocenter vector are expressed as,

$$\begin{aligned} X_{cm}(t) &= \frac{R_e}{M_e} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \cos\phi \cdot \cos\lambda \cdot L(\phi, \lambda, t) \cdot \Delta s \\ Y_{cm}(t) &= \frac{R_e}{M_e} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \cos\phi \cdot \sin\lambda \cdot L(\phi, \lambda, t) \cdot \Delta s \\ Z_{cm}(t) &= \frac{R_e}{M_e} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \sin\phi \cdot L(\phi, \lambda, t) \cdot \Delta s \end{aligned} \quad (2)$$

The surface mass load is in unit of g/cm^2 , and $\Delta s = R_e^2 \cdot \cos\phi \cdot \Delta\phi \cdot \Delta\lambda$ is the area element in unit of cm^2 . In terms of degree one unnormalized Stokes Coefficients ($C_{1,1}$, $S_{1,1}$, $C_{1,0}$), the above equations can be simplified as

$$\begin{aligned} X_{cm}(t) &= R_e \cdot C_{1,1}(t) \\ Y_{cm}(t) &= R_e \cdot S_{1,1}(t) \\ Z_{cm}(t) &= R_e \cdot C_{1,0}(t) \end{aligned} \quad (3)$$

Analysis by *Dong et al.* [1997] shows that the deformational effect on degree one spherical harmonics is very small (about 2 %), and a correction for deformation is therefore not applied in this paper.

2. DATA

2.1 Atmosphere models

Mass load variations due to the atmosphere are proportional to surface pressure variations. The surface pressure data are from the NCEP/NCAR Climate Data Assimilation System I (CDAS-1) [Kalnay et al., 1996]. The CDAS-1 monthly surface diagnostic fields covers from January 1958 through present. Pressures are given on a Gaussian grid of 1.875 degree in longitude and about 1.904 degree (uneven) in latitude. Surface mass load variations (in unit of g/cm^2) due to the atmosphere are computed by,

$$L_{atm}(\phi, \lambda, t) = \frac{\Delta P(\phi, \lambda, t)}{g} \quad (4)$$

where $\Delta P(\phi, \lambda)$ is surface pressure variation with respect to the long term mean at time t and g , the acceleration of gravity is assumed constant.

2.2 Sea level anomalies

The TOPEX/Poseidon (T/P) satellite altimeter has been providing accurate global measurements of sea level change for over five years. The T/P data used in this paper include cycles 2 through 168, which cover October 1992 through April 1997. Mass load variations are estimated from sea level anomalies using the T/P Geophysical Data Record (GDR), provided by the NASA Jet Propulsion Laboratory (JPL) with all media, instrument, and geophysical corrections applied [Callahan, 1993], including ionosphere delay, wet and dry troposphere delay, electromagnetic bias, tides, and inverted barometer response. In this study, Joint Gravity Model (JGM-3) derived orbits are applied to improve the orbit determination [Tapley et al., 1996], and the ocean tide model has been replaced with the UT/CSR 3.0 model [Eanes and Bettadapur, 1995].

Observed sea level variations over large spatial scales are a consequence of water mass redistribution and steric effects, including thermal expansion and salt advection. Thermal expansion associated with heat storage change in the ocean is the dominant steric effect. This part of sea level variation has virtually no contribution to mass load variations over the oceans. A simplified thermal expansion model [Chen et al., 1998] is applied to estimate seasonal steric sea level changes using the temperature fields in the NOAA World Ocean Atlas 1994 (WOA94) [Levitus and Boyer, 1994]. WOA94 provides $1^\circ \times 1^\circ$ objectively analyzed average temperature fields for the 12 months of the year for 19 layers from the surface to 1000 meters depth. Temperature variations relative to the annual mean temperature field are derived for the top 14 layers (0 to 500 meter depth, which covers most of the mixing layers in the ocean), and applied to estimate steric sea surface height changes for a given month. A $5^\circ \times 5^\circ$ two dimensional moving average filter has been applied to the steric sea surface height fields. The monthly fields of sea surface height changes introduced by steric effect are linearly interpolated to each T/P repeat cycle with the same spatial resolution we used in T/P sea level anomaly data ($1^\circ \times 1^\circ$), and then removed from the observed sea level anomaly fields. The mass load variation (in unit of g/cm^2) over the ocean is determined by,

$$L_{ocean}(\phi, \lambda, t) = \Delta H(\phi, \lambda, t) \cdot \rho \quad (5)$$

where ΔH is sea level change relative to the mean after the estimated steric effect is removed, and ρ is the mean density of sea water.

2.3 Hydrological model

Mass redistribution on land due to the global continental hydrological cycle has been conventionally investigated using precipitation, evapotranspiration, and surface runoff data [Hinnov and Wilson, 1987; Kuehne and Wilson, 1991; Lei and Gao, 1992], either from quite sparse meteorological observations, or from simplified hydrological models. In this study, we employ a new approach to estimate continental water storage changes using the assimilated soil moisture and water equivalent snow accumulation fields from CDAS-1 [Kalnay et al., 1996]. The monthly surface diagnostic soil moisture fields contain two layers, which cover the top two meters of soil (0 - 10 cm, 10 - 200 cm). The spatial resolution is described by the same Gaussian grid for surface pressure fields. Water content is represented by volumetric fraction, and total water storage changes (in g/cm^2) for a given grid point are estimated by integrating water content in the two soil moisture layers, and the water equivalent snow fields, as

$$L_{soil}(\phi, \lambda, t) = \sum_{i=1,2} \eta_i(\phi, \lambda, t) \cdot h_i \cdot \rho_o \quad (6)$$

$$L_{snow}(\phi, \lambda, t) = \Delta N(\phi, \lambda, t) \quad (7)$$

where η_i is the volumetric soil moisture value for layer i ($i=1,2$); h_i is the layer depth ($h_1 = 10$ cm, and $h_2 = 190$ cm); and ρ_o is water density. Variations of snow water (ΔN give directly the mass load variations (in g/cm^2).

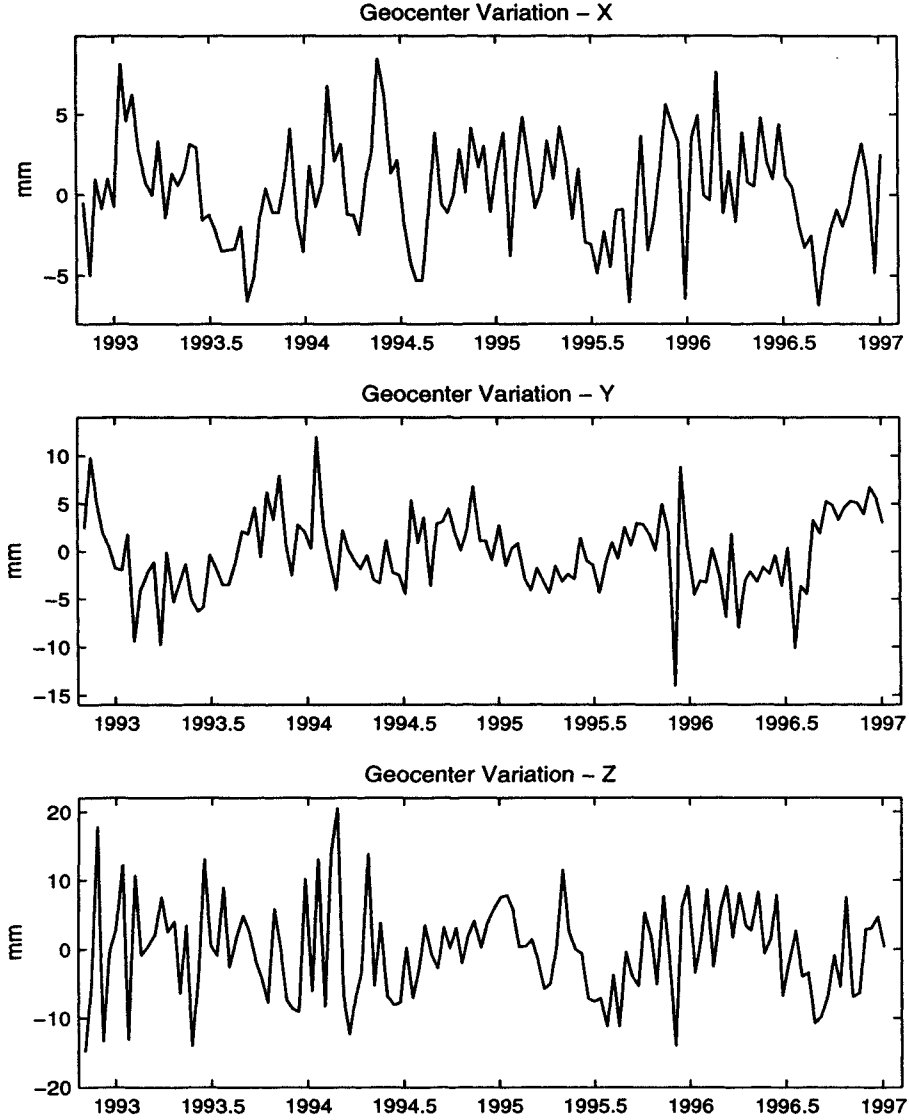


Figure 1. Observed geocenter motions in the X, Y, Z components estimated from orbital residual analysis of Lageos 1 and 2 SLR data [Eanes et al., 1997].

2.4 Observed geocenter motions

Geocenter variations are determined from a combination of Lageos SLR data. Translational motion of the ITRF with respect to the mass center of the Earth can be determined from SLR orbital residual analysis with major error sources being mismodeled non-gravitational accelerations and orbital effects of time variable spherical harmonics of degrees greater than one [Eanes et al., 1997]. A four year time series of geocenter solutions using 12-day intervals was determined from a combination of Lageos-1 and Lageos-2 SLR data. Figure 1 shows the three components of observed geocenter variations from Lageos 1/2. The amplitude and phase of annual and semiannual variations are listed in Table 1. Uncertainty is estimated to be ± 3.5 mm in X, ± 3.8 mm in Y, and ± 8.6 mm in Z. The poorer determination of the Z component is a result of the geometry of the Lageos orbit and the distribution of the SLR stations. Observed geocenter motion shows both clear seasonal signals and a broad band of high frequency

variations. An interesting question is whether these high frequency variabilities are real signal or noise.

3. RESULTS AND COMPARISONS

3.1 *Atmospheric contributions*

The three components of predicted geocenter variations due to atmospheric pressure are shown in Figure 2. The atmosphere appears to be responsible for much of the variability in the Y component due to the distribution of ocean/land, while its contributions to the X and Z components appear less important. Table 1 provides quantitative comparisons for annual and semiannual components, and shows that there is reasonably good agreement with annual terms given by *Dong et al.* [1997] in both amplitude and phase (see Table 1).

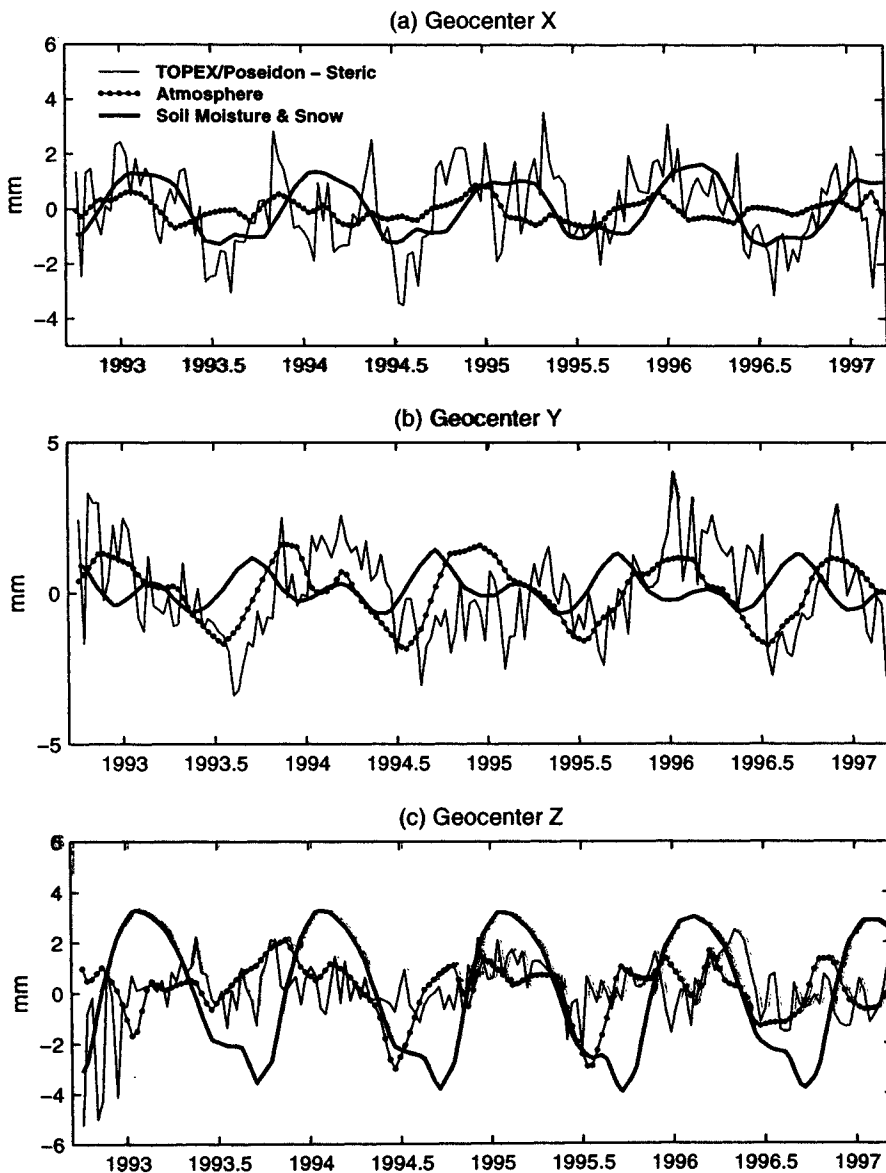


Figure 2. Geocenter variations in the X, Y, and Z components introduced by atmospheric surface pressure, continental water storage, and oceanic mass changes. These geophysical predictions are computed using CDAS-1 assimilation system and TOPEX/Poseidon data after a steric correction is applied based on WOA94.

3.2 *Continental hydrological effects*

Geocenter motions predicted from continental water storage change are also shown in Figure 2, with seasonal components in Table 1. The results indicate that the continental hydrological cycle provides significant contributions to the X and Z components, especially Z. The continental hydrological cycle accounts for over half of the observed annual variation in the X component and has nearly the same phase (see Figure 5 and Table 1), and appears to be the dominant contributor to the Z component. The hydrological model predictions from this study are different to the results given by *Dong et al.* [1997] in the X and Y component (see Table 1 and Figure 5), while the agreement in Z is very good in both amplitude (3.30 mm vs. 3.56 mm) and phase (43 degree vs. 40 degree, see Table 1 for phase definition).

3.3 Contributions from the oceans

The potential oceanic contributions computed from T/P sea surface anomalies are shown in Figure 2, along with atmospheric and hydrological predictions. Mass variations within the oceans account for a major part of the observed geocenter variations in the X and Y components, especially the X component. This is mainly because the geographical orientation of the oceans is close to the X direction (Greenwich meridian). There is a good correlation in X between observed geocenter motion and T/P prediction at a wide range of frequencies. Figure 3 shows the estimated cross correlations after seasonal variations (annual and semiannual) are removed from both series. The agreements in Y and Z are relative worse. The annual variation in the X component (1.0 mm and 73 degrees) is in very good agreement with *Dong et al.*'s estimation (1.1 mm and 79 degrees) from ocean bottom pressure using the ISO ocean circulation model (see Figure 4 and Table 1).

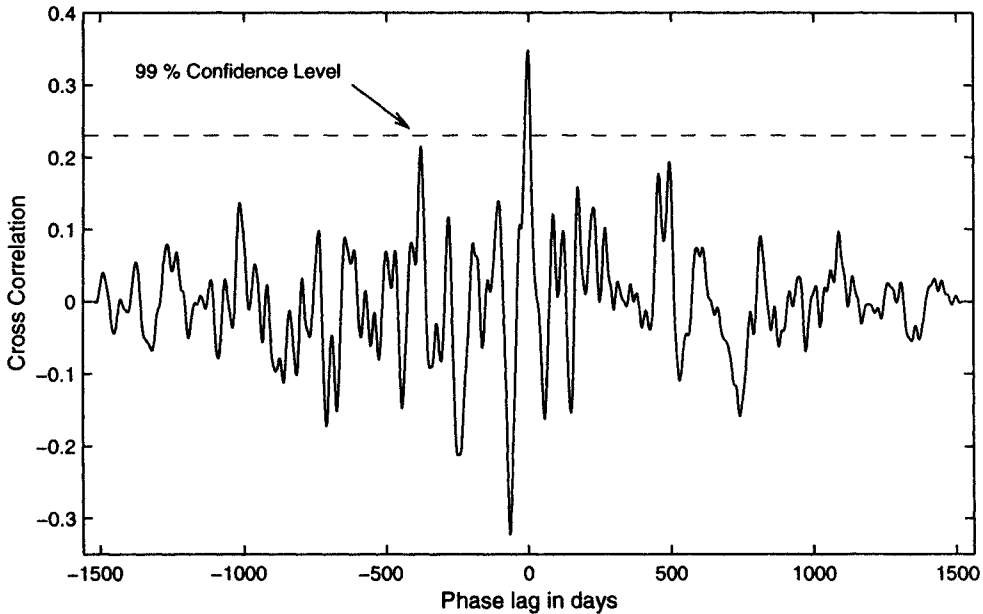


Figure 3. Cross correlation between Lageos geocenter solution in X and the corresponding oceanic contributions from TOPEX/Poseidon. The annual and semiannual variations are removed from both series.

3.4 Overall budget of geocenter variations

The X, Y, and Z components of combined geocenter variations caused by mass variations in geophysical fluids, including atmospheric pressure, the continental hydrological cycle, and sea level anomalies are shown in Figure 4, and compared with the Lageos observations. The annual and semiannual variations of each component are listed in Table 1. We have also calculated total annual variations for the three major contributors given by *Dong et al.* [1997]; however, we omit the ocean tidal effect which is about two orders of magnitude smaller. Figure 5 shows vector representations of seasonal geocenter variations from Lageos solution, atmospheric pressure, the

continental hydrological cycle, and ocean mass redistribution for the three components. The overall seasonal variations estimated from *Dong et al. [1997]* are also included.

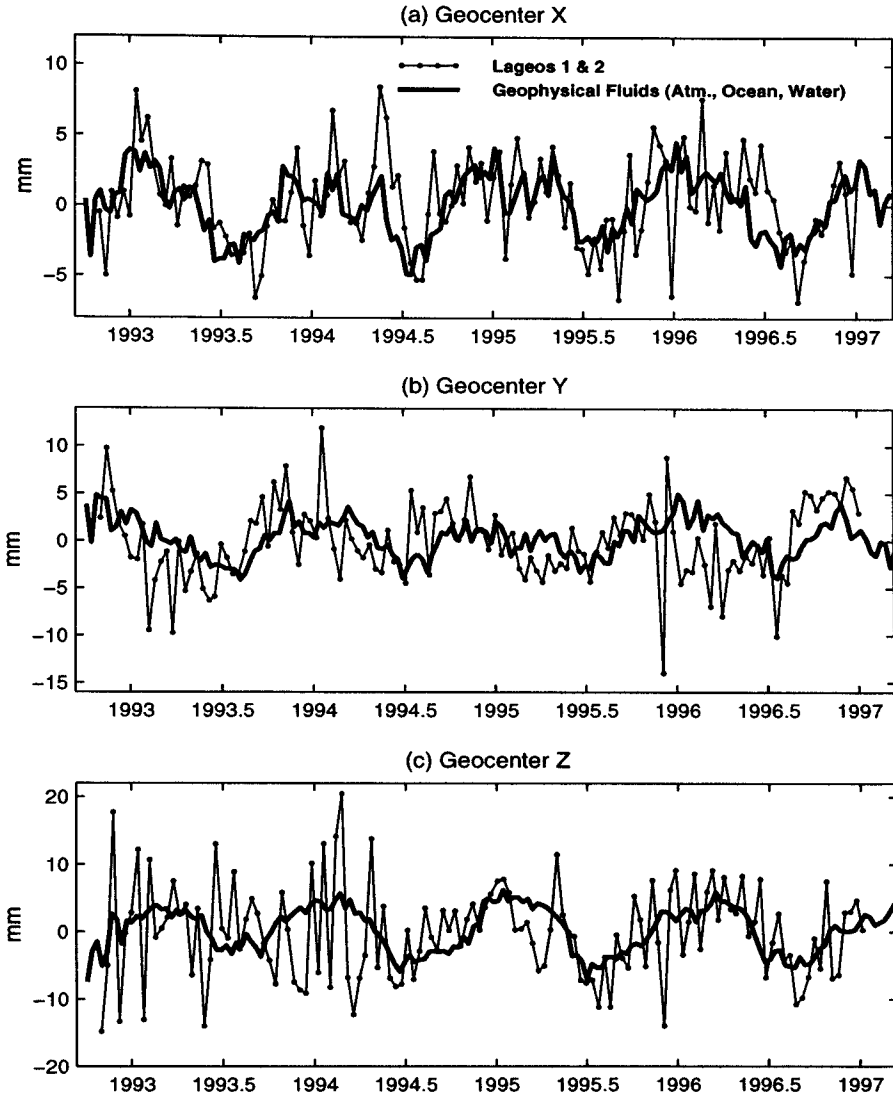


Figure 4. The total budget of geocenter variations from atmospheric pressure variations, continental water storage changes, and sea level variations, comparing to the observed geocenter variations from Lageos 1/2.

4. DISCUSSIONS

Comparisons of observed geocenter motions with the predicted effects of geophysical fluids indicate that the atmosphere, the continental hydrological cycle, and the oceans are all important contributions. The atmosphere is predicted to make large contributions to the Y component, while the oceans tend to dominate in the X component over a wide range of frequencies. This is mainly due to the orientation of continents along Y and the oceans along the X direction. The continental hydrologic cycle provides significant contributions to X and Z, especially the Z component. Large seasonal variability (about 3.3 mm) in the Z component is due to the out of phase seasons in the two hemispheres.

The good correlation (well above 99 % confidence level) of non seasonal variations in the X component between observed geocenter motions and T/P ocean mass predictions (see Figure 3) is a strong indication that some of the sea level anomalies determined from TOPEX/Poseidon

altimeter data are from ocean mass redistribution. This conclusion is supported by other investigations of gravity field variations, earth rotation, and the global water mass balance [Chen et al., 1997, 1998].

Table 1. Annual and semiannual variations observed from Lageos 1 and Lageos 1/2, and estimated from atmosphere, continental hydrological cycle and sea level variation compared with the estimates given by Dong et al. (1997). The sign and phase errors in Dong's land water components have been corrected (personal communication).

Sources		Annual		Semiannual	
		amplitude (mm)	phase (deg)	amplitude (mm)	phase (deg)
Lageos 1/2 [Eanes et al., 1997]	x	2.18	31	1.08	164
	y	3.20	151	0.77	213
	z	2.79	45	0.38	13
Pressure (ECMWF) [Dong et al., 1997]	x	0.55	104	0.23	90
	y	1.31	91	0.38	217
	z	0.87	133	0.73	271
Pressure (CDAS-1) [This study]	x	0.37	116	0.16	100
	y	1.26	94	0.41	217
	z	0.80	100	0.75	252
Land water (P-E-R) [Dong et al., 1997]	x	3.28	25	0.84	319
	y	2.94	185	0.94	48
	z	3.57	40	0.66	344
Land water (Soil/snow) [This study]	x	1.28	44	0.15	331
	y	0.52	182	0.56	312
	z	3.30	43	0.50	75
Oceans (ISO model) [Dong et al., 1997]	x	1.05	79	0.39	248
	y	0.09	121	0.29	282
	z	0.18	218	0.16	41
Oceans (T/P) [This study]	x	0.96	73	0.86	187
	y	0.97	52	0.73	173
	z	0.49	3	0.25	232
Total [Dong et al., 1997]	x	4.22	44	0.83	30
	y	3.19	159	0.43	26
	z	3.46	55	1.10	313
Total [This study]	x	2.38	64	0.75	181
	y	2.00	90	0.89	221
	z	4.10	48	0.50	238

Note: The phase is defined as following: 0 refers to 0h Jan 1. Steric correction is applied to TOPEX/Poseidon data.

Our atmospheric estimates are in reasonably good agreements with the results given by Dong et al. [1997]. The slight discrepancy is possibly due to the use of different atmospheric models and differences in integration algorithms, land mask definitions, and treatment of the inverted barometer over the oceans. There is good agreement between these two studies in the predicted ocean contribution to the X component. The annual variation estimated from T/P altimeter data is nearly identical to the ISO ocean bottom pressure approach described by Dong et al. [1997]. However, predicted ocean contributions to the Y and Z components do not agree well. These discrepancies could be caused by the mismodeled mass distribution in the ocean general circulation model, or the mismodeled geophysical corrections to T/P altimeter data.

Predicted geocenter variations due to continental water storage change using CDAS-1 assimilated soil moisture and snow fields are generally quite different from estimates given by

Dong et al. [1997] using a traditional precipitation, evaporation, and runoff budget, except for the Z component. Phases agreement is relatively good. (See Table 1). The agreement appears reasonable if considering our poor knowledge of the global hydrological cycle. Many error sources may contribute to the discrepancies, including the mismodeled evapotranspiration and runoff in the traditional approach, and assimilated soil and snow fields due to lack of observational input. The soil water change under 2-meter depth and water exchange between soil water and ground water could also be major error sources.

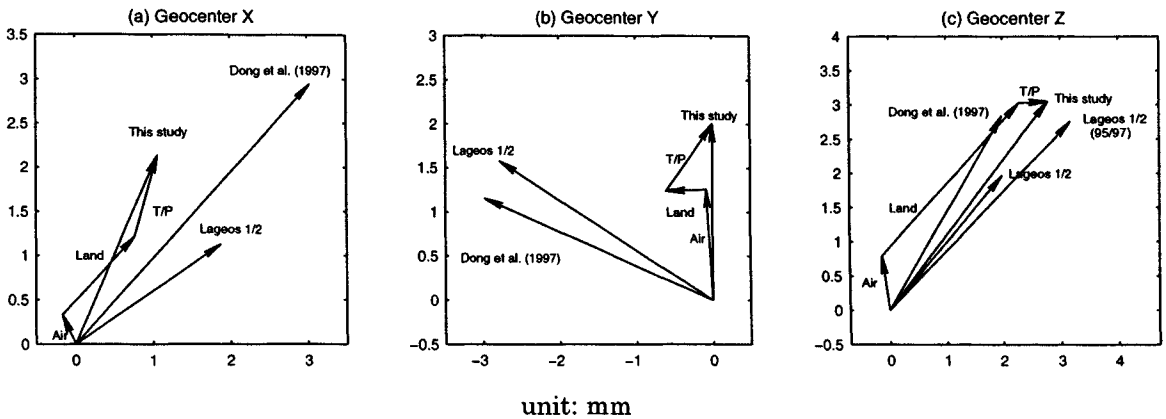


Figure 5. Vector representation of seasonal geocenter variations of the three components (X, Y, Z). The results from this study are shown together with Lageos-1/2 solution and the estimates given by *Dong et al.* [1997] (The sign and phase errors in *Dong et al.* [1997] are fixed). Lageos 1/2 (95/97) is computed from the last two year's data (Jan. 1995 - Jan. 1997) of Lageos 1/2 solution [Eanes et al., 1997].

Accurately determined geocenter variations and a full understanding of the observed geocenter motions provide important information about mass redistribution in the Earth system, and should provide observational constraints on mass budgets in global atmospheric and hydrological models, especially snow/ice accumulation and melt in Antarctic, Arctic, and Greenland, which are of great interest for studies of global climate change. Geocenter variations are also important in establishing a more accurate ITRF system, which influences virtually all geodetic observations.

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We are grateful to Don Chambers for providing TOPEX/Poseidon sea surface anomaly data, and B.D. Tapley, C.K. Shum, and B.F. Chao for helpful discussions. This research was supported by the National Aeronautics and Space Administration under the grants NAGW-2615 and NAG5-3129.

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GEOCENTER VARIATIONS FROM ANALYSIS OF TOPEX/POSEIDON SLR DATA

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INTRODUCTION

The global-scale fluid-motions produce temporal variations in the Earth's gravity field and the geocenter. The geocenter variation is the motion of the origin of the Terrestrial Reference Frame (TRF) with respect to the center of mass of the Earth system. Space geodetic measurements, such as the SLR (satellite laser ranging) and DORIS (Doppler Orbitgraphy and Radiopositioning Integrated from Space), link a satellite, which orbits about the center of mass of the Earth system, and the tracking sites, which realize the TRF. Thus, the satellite tracking data provide a unique capability for measuring the geocenter variations.

The temporal and spatial distribution of the tracking data for a satellite plays a significant role in its ability to sense the geophysical signals from the Earth. Recent estimates of the annual variations in the geocenter are at the millimeter level. To determine such small geocenter variations, centimeter level orbit fits are required in addition to the requirement for global and intensive tracking of a satellite. The TOPEX/Poseidon (T/P) satellite is nearly continuously tracked by both SLR and a globally well distributed DORIS network. The average number of SLR normal point observation per orbit revolution for T/P satellite is about 1.5 times more than that of the Lageos-1 satellite [Kar, 1997]. Using available state-of-the-art satellite force and measurement models [Tapley et al., 1994], the average laser ranging residual RMS for a 10-day TOPEX orbit fit is 2 cm, which is comparable with Lageos-2, and smaller than the RMS of 4-5 cm for Lageos-1 and Starlette. The large RMS for the Lageos-1 orbit fit is caused by the non-gravitational eccentricity excitation, which changes rapidly in magnitude with time. The complicated shape of TOPEX makes it more difficult for modeling the nongravitational forces than those spherical geodetic satellites, but adjusting the epoch satellite initial conditions along with the 8-hour C_T and daily once-per-rev acceleration parameters for transverse and normal component results in a good fit to the observations. The intensive tracking of T/P satellite makes such estimation possible for reducing the orbit error. The results reported to IERS 1997 campaign for the geocenter variations from analysis of SLR tracking data to the T/P satellite is briefly discussed in following sections.

SOLUTION METHOD

The position vector, $\vec{r}$, of an Earth orbiting satellite in the inertial frame can be defined as

$$\vec{r} = \vec{\rho} + \vec{R}_s + \vec{r}_{cm}$$

where $\vec{r}_{cm}$ is the vector from the center of mass of the Earth system to origin of the TRF, $\vec{R}_s$ is the position vector of a tracking station in the TRF, $\vec{\rho}$ is the slant vector from tracking site to satellite. The unmodeled geocenter variations will result in the observation residual, which is the difference between the observed and computed slant range from the reference orbit with best fit to measurements. In this study, a post-fit approach is used to estimate the geocenter using observation residuals over a 10-day time span assuming that the observation residuals are mainly due to measurement model errors, including the geocenter variations, range biases, earth orientation parameter (EOP) errors etc. The observation residuals used in this study were based on the TOPEX reference orbit used to determine the mean sea surface topography with a RMS of 2 - 3 cm. The dynamical characters of the reference orbit are fixed. The range bias for some tracking stations over a longer time span, and the orbital element corrections and

EOP over a short arc are adjusted to reduce the orbit errors to some degree. Analysis of the 10-day time series for the geocenter variations determined from 176-cycle T/P SLR residuals shows that seasonal geocenter variations are observable, and particularly significant in the Y component. Table 1 shows the amplitude and phase for the annual (*Sa*) and semiannual (*Ssa*) geocenter variations estimated from the 15-day time series derived from T/P SLR data.

Table 1 Annual and Semiannual Variations of Geocenter from T/P SLR Data

	X		Y		Z	
	Amp (mm)	phase (deg)	Amp (mm)	Phase (deg)	Amp (mm)	Phase (deg)
<i>Sa</i>	2.1	309	4.7	97	1.3	329
<i>Ssa</i>	0.3	159	0.5	139	0.1	26

DISCUSSION

A dynamic orbit fit approach was used to verify the T/P results for the geocenter variations obtained from the post-fit approach. In dynamic approach, the position vector of the geocenter is simultaneously estimated with the initial conditions of the satellite and the dynamic parameters (drag coefficients and other empirical acceleration parameters) to be the best fit to the observations. Comparison of the annual and semi-annual geocenter variations determined using TOPEX SLR data shows that the phases agree within 10 degree from the two approaches. Amplitudes are increased by approximate 40% for the annual variations in the X and Y components. A 9.8 millimeters amplitude for the annual variation in the Z component from the dynamic approach was found, which indicates that the geocenter variations in the Z component are not separable from the once-per-rev orbit errors. The interesting signals for geocenter variations were effectively absorbed by estimating the once-per-rev parameters in the process of generating reference orbit. The high frequency orbit errors cause the scattering of solution from the dynamic approach. The facts suggest that the accuracy of the current estimates for geocenter variations is limited by the aliasing effects on the geocenter variations, particular for the Z component, from the once per revolution orbit errors for T/P orbit.

In conclusion, the millimeter level magnitude of the geocenter variations is smaller than the current accuracy of orbit fit. The T/P results for the annual geocenter variations are comparable with the results from the combination of Lageos 1 and Lageos 2 [Eanes et al, 1997] except for the Z component. Improved non-gravitational force models are required to improve the estimates for geocenter variations from satellite tracking data.

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CGS GEOCENTER TIME SERIES FROM SLR AND GPS DATA

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The “geocenter motion” is the translation motion of the Earth’s centre of mass as viewed from a crust fixed frame. In order to estimate the “geocenter motion” we have analysed SLR and GPS data with different approaches to define the best analysis procedure for the estimation of this parameter.

The name used to identify the different data analysis procedures are absolutely conventional for this document; we defined “geometric” and “gravitational” the procedures used in SLR data analysis, while the methods used in GPS data analysis are defined as “geometric” and “direct”. With the “gravitational” and the “direct” methods we directly estimate the time series of the “geocenter motion”, while following the “geometric” method these parameters are obtained by a Helmert transformation of the coordinates of the stations estimated in the analysis to the ITRF94.

SLR DATA ANALYSIS

The models adopted in the SLR data analysis generally follow the IERS conventions (McCarthy D., 1996) with the exception of the Earth gravity model since the EGM96 is used. We have analysed the same data set with two different approaches: the “geometric” and the “gravitational”.

“Geometric” method

The results reported have been obtained from the analysis of Lageos I and Lageos II SLR data available from January 1993 to December 1996. The software used is the NASA/GSFC GeodynII

In the EGM96 gravity model the coefficients of first degree are equal to zero which means that the centre of mass of the Earth coincides with its centre of volume; this allows to obtain the geocenter motion as a series of translation parameters (T_x, T_y, T_z) between the origin of the Terrestrial Reference Frame (TRF) realised by the SLR stations in each data reduction batch and the origin of ITRF94.

The station coordinates are estimated combining Lageos I and Lageos II data in independent 14-day batches. In addition to station coordinates, we estimate daily EOP, satellites ephemerides, station biases and along-track accelerations with a free-network approach (Heflin M.B. et al, 1992) weakly constraining the apriori station coordinates with a 10 meters sigma. The station velocities are held fixed at the ITRF94 values.

Following a free-network approach, for each solution we obtain a loosely defined internal references frame; a tight defined internal references frame could be obtained through the applications of internal constraints (rotational, translation and scale elements) to the covariance matrix obtained from the reduction procedure. The adopted mathematical procedures are described in Heflin M.B. et al., [1992], Gregorius T. [1996].

In order to obtain a homogeneous series of translation parameters any solution is then transformed into the ITRF94 frame by a Helmert transformation.

The minimal constraints application and the Helmert transformation have been performed using GIPSY-OASIS II tools (Webb F.H. et al, 1995)

The mean offsets with respect to ITRF94 for the three series are:

Tx series: wmean = -3.477 mm, wrms = 5.506 mm

Ty series: wmean = -7.864 mm, wrms = 9.463 mm

Tz series: wmean = 11.161 mm, wrms = 17.811 mm

The translation parameter series (Tx,Ty,Tz) obtained by these transformations are shown in fig.1

The free-network approach in data minimises the possibility to introduce frame errors; but, in order to have good results, it needs a well distributed global network and high quality data for each station. The outliers present in the estimated Tx, Ty and Tz series are due to bad configurations of the analysed network.

“Gravitational” method

In this SLR solution, the data set covers the same period of the previous solution (January 1993 - December 1996), the software used is the NASA/GSFC Geodyn II/Solve.

The analysis procedure can be divided into two phases: arc solution and global solution.

In the arc solution we separately analyse the data of Lageos I and Lageos II satellites in 14-day independent batches; the normal equations are built up for all the parameters to be estimated but, at this stage, they are solved only for the parameters related to the orbit (state vectors and empirical along-track accelerations) and to the laser tracking network (station range bias).

In a global solution all the matrices are combined with Solve in a global matrix; the Terrestrial References Frame is defined by fixing the ITRF94 coordinates of Greenbelt (7105) and Herstmonceux (7840). The global matrix is inverted by Solve to estimate the site position at a references epoch (1993.0), the daily EOP parameters and the C_{10} , C_{11} , S_{11} geopotential coefficients every 14 days.

These coefficients are proportional to global translation of the terrestrial references system and therefore they describe the motion of the geocenter.

The Tx, Ty and Tz series are obtained from C_{10} , C_{11} , S_{11} applying the following equations (Heiskanen W.A. et al, 1966):

$$\begin{aligned} Tx &= \alpha \cdot \bar{C}_{11} \cdot \sqrt{3} \\ Ty &= \alpha \cdot \bar{S}_{11} \cdot \sqrt{3} \\ Tz &= \alpha \cdot \bar{C}_{10} \cdot \sqrt{3} \end{aligned} \quad (1)$$

$\alpha = 6378.1364$ Km is the mean terrestrial radius.

These values represent the coordinates of the center of mass in the TRF used in Solve.

In order to have time series comparable to those obtained with the “geometric” method we calculate the Helmert transformation parameters between this TRF and ITRF94. The values of this translation are added to those obtained by (1).

The Tx,Ty and Tz offsets, in terms of wmean and wrms with respect to ITRF94, are:

Tx series wmean = -6.253 mm, wrms = 8.438 mm

Ty series wmean = -3.243 mm, wrms = 6.093 mm

Tz series wmean = 15.306 mm, wrms = 21.704 mm

The series are shown in figure 1.

Comments

The two time series obtained from SLR data analysis show a good agreement in terms of signal content but in the series obtained with the “gravitational” method the statistical error in the XY plane is 3 times lower than the estimated error in the series obtained with the “geometric” method and in the Z direction the error improvement is of the order of 40%.

GPS DATA ANALYSIS

We use two different analysis approaches also in the GPS data analysis using the GIPSY-OASIS II software (Webb.F.H., et al, 1995). In both solutions, here defined as “geometric” and “direct”, we have generally adopted the models recommended in the IERS conventions (McCarthy D., 1996). For the solid Earth tide we have used the Williams model. The analysed data set (daily Rinex observations compressed in 5 minutes NP) covers the period from 14 July 1996 to 11 January 1997 (six month of data) coming from a network of stations selected considering a global and homogeneous distribution.

The entire data set has been analysed in daily batches.

In the two solutions we solve for the following parameters: satellites and station clocks (one clock has been kept fixed as reference), tropospheric zenith path delay, phase ambiguity, satellites state vectors, solar radiation pressure, pole coordinates and rates, UT1-UTC rate.

“Geometric” method

The “geometric” method estimates the station coordinates using a free-network approach with apriori sigma to station coordinates from 10 meters to 1 km (Vanicek P. et al 1986).

Each daily independent station coordinate estimation is then transformed into a defined references frame following the same procedure described for SLR: minimal inner constraints using the full estimated covariance matrix and Helmert transformation.

The Tx, Ty, Tz series obtained with this transformation give the geocenter motion.

The offsets obtained in the three GPS series with respect to ITRF94 are:

Tx series: wmean = 0.100 cm, wrms = 4.741 cm

Ty series: wmean = 1.200 cm, wrms = 7.281 cm

Tz series: wmean = -7.771 cm, wrms = 14.770 cm

“Direct” method

The “direct” method directly estimates, in addition to the parameters previous described, the offset between the centre of mass of the Earth and the ITRF94.

In this procedure we used 17 stations globally distributed whose coordinates have been kept fixed at the ITRF94 values and propagated at each epoch of the analysed data.

The wmean and wrms obtained for the series of this solution are:

Tx series: wmean = -2.331 cm, wrms = 4.860 cm

Ty series: wmean = 0.910 cm, wrms = 4.951 cm

Tz series: wmean = -6.871 cm, wrms = 8.920 cm

Comments

The two series of parameters (figure 2) obtained from GPS are quite comparable; they show a good agreement in the Tx and Ty series even if the Ty series obtained with the ‘geometric’ method is a little bit noisy. In the Tz series it is evident that the results obtained with the ‘direct’ method are better.

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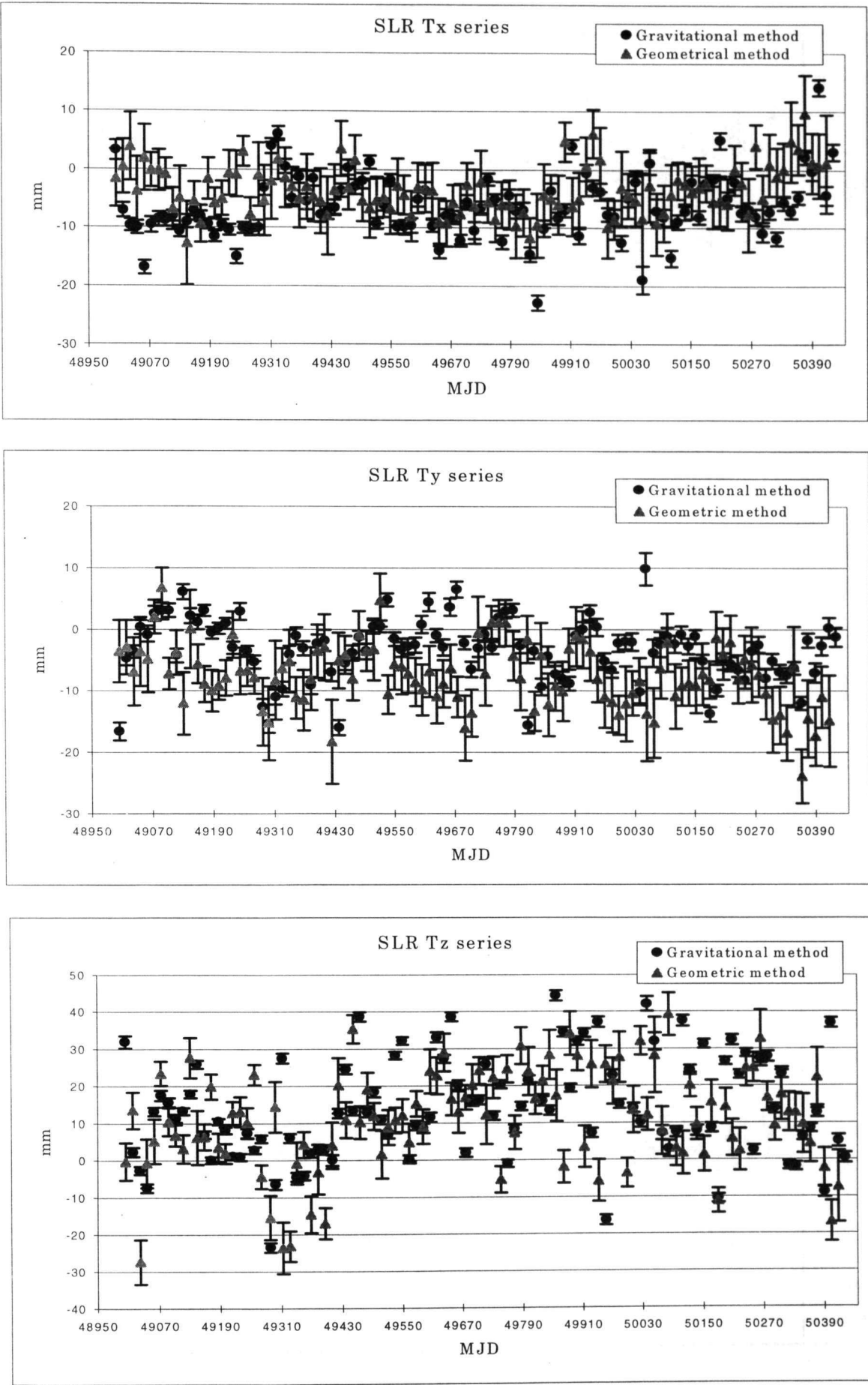


Fig. 1 The two time series obtained from SLR data analysis show a good agreement in terms of signal content. With the “gravitational” method the statistical error in the XY plane is 3 times lower than the estimated error in the series obtained with the “geometric” method and in the Z direction the error improvement is of the order of 40%.

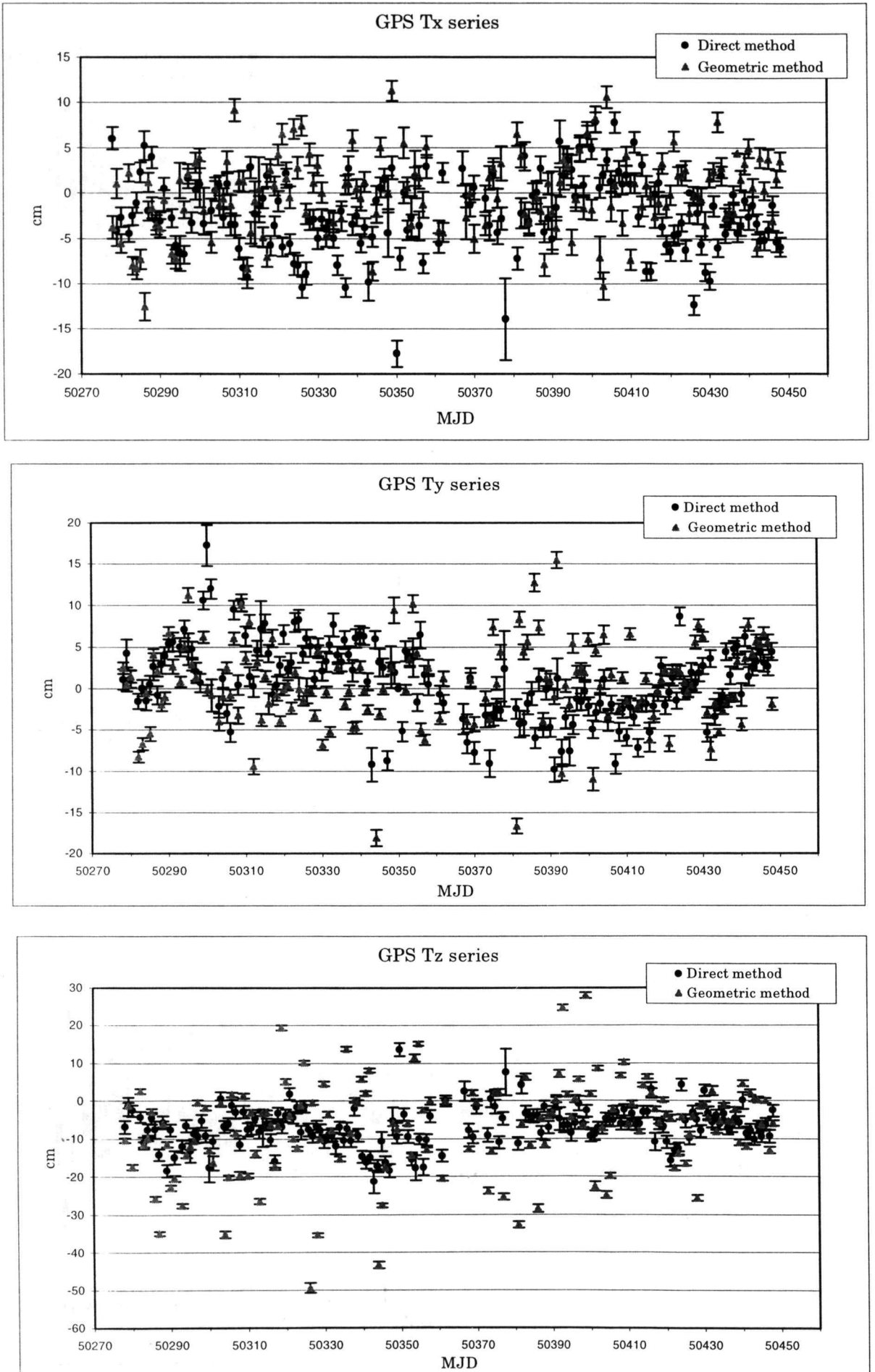


Fig. 2 The two series of parameters obtained from GPS are quite comparable; they show a good agreement in Tx and Ty series even if the Ty series obtained with the 'geometric' method it's a little bit noisy. In the Tz series it is evident that the results obtained with the 'direct' method are better.

GEOCENTER VARIATIONS CAUSED BY MASS REDISTRIBUTION OF SURFACE GEOPHYSICAL PROCESSES

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Abstract: Both surface and internal mass redistribution causes geocenter variations. The global surface mass redistribution can be measured or modeled and is considered as the primary contributor to the geocenter variations on seasonal time scale. Once the geocenter variations from satellite measurements and from the surface mass load contributors are determined with sufficient accuracy, the residuals between the two will provide important constraints on the mass redistribution from various internal processes. Our results [Dong *et al.*, 1997] suggest that on the time scale from 30 days to 10 years the primary variability of geocenter variations from atmosphere, ocean and surface ground water occurs on the annual and semiannual scales. The lumped sum of these surface mass load induced geocenter variations is within 1 cm level. Preliminary comparison between our geophysical model predicted and satellite (SLR, GPS) measured geocenter variations shows fairly good agreement for annual component; however, not for semiannual component.

1. SUMMARY OF OUR PREVIOUS WORK

We define the geocenter as the center of figure (CF) of the Earth relative to the center of mass (CM) of the Earth including mass load [Dong *et al.*, 1997]. If the origin of our terrestrial reference frame is defined by a set of tracking stations with sufficient global coverage, the variations of the network center will be a good representation of the geocenter variations. Theoretically the spectrum of the geocenter variations is as rich as the sum of spectra from various geophysical processes which are capable of causing mass redistribution. The relation between the geocenter position vector $\mathbf{r}_{CF}$ (defined in CM frame) and the geophysical process induced surface mass load position vector $\mathbf{r}_{CF}$ (defined in the Earth-fixed reference frame) is

$$\mathbf{r}_{CF} = - \left(1 - \frac{h_1 + 2l_1}{3}\right) \frac{M_l}{M_e + M_l} \bar{\mathbf{r}}_{load} \quad (1)$$

where M_e and M_l represent the mass of Earth (without load) and mass of load respectively, $h_1 = -0.290$ and $l_1 = 0.113$ [Farrell, 1972], indicating that the deformation slightly enlarges

the amplitude of r_{CF} by about 2.1%. Recent discussion about the relation between the degree one mass load Love number and the reference frame was provided by Grafarend [1997].

Geocenter variations caused by atmosphere, ocean and surface ground water were calculated. On the time scale from 30 days to 10 years, the primarily variability of the geocenter variations from these contributors occurs on the annual and semiannual scales. A sign error in the z-component of the groundwater inferred geocenter variation series of *Dong et al.* [1997] is corrected here. Also, the time tags of the groundwater inferred geocenter variation series should use the middle epochs of each month instead of the first day of the month to better represent the monthly mean time series; this modification affects the phases of all groundwater components. The revised Table 1 and Figure 4 of *Dong et al.* [1997] are given here as Table 1 and Figure 1, indicating that ground water is the largest contributor to all three components at the annual period and both x and y components at the semiannual period. The atmosphere is the largest contributor for the semiannual z component with ground water being about 10% less. Unfortunately, the mass redistribution of the surface ground water is the least understood contributor and deserves substantial further study. The total annual terms are considerably larger than the corresponding semiannual terms by a factor of 6.7, 7.6, 2.7 for x, y, z components respectively (see Table 1). The x, y components of geocenter variations from seasonal to interannual time scales are likely within 1 cm level unless these time series have significant errors, we omitted some important surface mass load contributors, or the internal mass redistribution processes play a dominant role.

Table 1. Annual and Semiannual Geocenter Variations from Surface Mass Redistributions

source*		Annual		Semiannual	
		Amp ⁺ . (mm)	Phase ⁺ (deg.)	Amp ⁺ . (mm)	Phase ⁺ (deg.)
Atmosphere	x	0.55	284.1	0.23	270.4
	y	1.31	270.7	0.38	36.8
	z	0.87	312.8	0.73	90.7
Ocean non-tidal	x	1.05	258.8	0.39	67.7
	y	0.09	301.0	0.29	101.9
	z	0.18	37.7	0.16	220.6
Ocean tide	x	0.03	87.6	0.21	290.8
	y	0.003	267.6	0.02	110.8
	z	0.03	267.6	0.21	110.8
Ground water	x	3.28	204.8	0.84	139.4
	y	2.94	4.6	0.94	228.2
	z	3.57	220.2	0.66	163.6

* ECMWF data are used for atmosphere. Isopycnal ocean circulation model is used for ocean non-tidal. Self-consistent equilibrium Sa and Ssa tide models are used for ocean tide.

⁺ Amplitude A and phase ϕ are defined by $A \sin[\omega(t-t_0)+\phi]$ where t_0 is January 1, 1990, ω is the frequency.

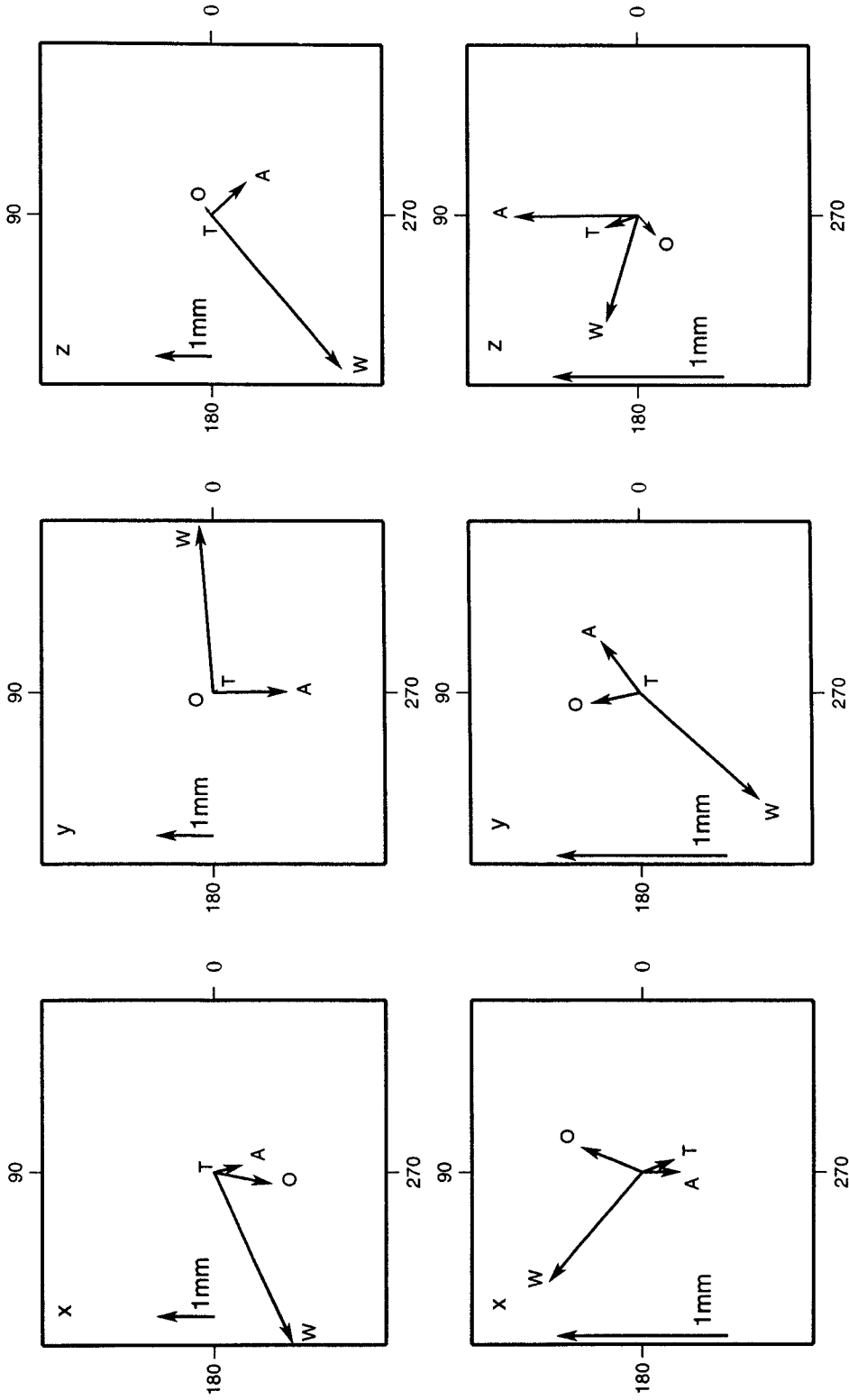


Figure 1: Annual (first row) and semiannual (second row) components of geocenter variation. The notations are: A atmosphere, O ocean current, T ocean tide, W surface ground water. The phase is referred to Jan. 1 with sine convention.

One missing contributor in our previous work is the mass redistribution due to the ice sheet volume and snow cover variations over the land due to lack of data with sufficient resolution on seasonal time scales [Trupin *et al.*, 1992]. The RAND data set of the global snow depth [Schutz and Bregman, 1988] infers 2.2 mm annual geocenter variation in z component due to the snow redistribution in the polar region. Satellite-borne radar altimeter data provide another tool to measure the mass variation of the ice sheet. Such a data can reveal seasonal scale variations of the ice sheet volume if the orbital errors can be eliminated effectively [Yi *et al.*, 1997]. For a diagnostic test, we consider a simple case: 10 cm averaged seasonal surface height variation in Greenland and 5 cm averaged seasonal surface height variation in Antarctica. Assuming the density of the compact snow is 400 kg/m^3 , the inferred amplitudes of the seasonal geocenter variations for x , y , z are 0.072, 0.063, 0.328 mm for Greenland and 0.023, 0.067, 1.022 mm for Antarctica. This indicates the primary contribution of this source is to the z component and likely less than 1 cm level.

2. COMPARISON WITH SATELLITE DETERMINED GEOCENTER VARIATIONS

Current space-geodesy techniques have captured signals of the geocenter variations from diurnal and semidiurnal bands [Watkins and Eanes, 1997] to seasonal or even longer period [Kar, 1997]. Special attention should be paid to the measurement of the secular geocenter variation. Since a considerable portion of the secular geocenter variation has been absorbed by the terrestrial velocity reference frame, directly measured secular motion of the global network center will represent the unmodeled part of the secular geocenter motion. Our study is focused on the seasonal time scales. To compare with the geophysical processes inferred geocenter variations on seasonal scales, we choose satellite determined seasonal variations of geocenter from three independent sources: the solution from the combination of LAGEOS I and LAGEOS II SLR data [Eanes *et al.*, 1998], the solution from Topex SLR data [Cheng, 1998], and the solution from GPS data [Zhu *et al.*, 1998]. The details of the satellite determined solutions can be found in the corresponding papers (in this report issue). Since the satellite determined solution adopt the definition of CM relative to CF as the geocenter position, we change the sign of these solutions to make the solutions consistent with our definition.

The comparisons of the annual and semiannual components are shown in Figure 2 and Figure 3 respectively. Since the GPS solutions used here are a factor of two larger than the other solutions, we scale the GPS solutions by 0.5 in order to use a common scale in the Figures. For the annual x component, all the three satellite derived solutions show strong agreement in phase with our solution, with the maximum phase difference being within 12 degrees. The GPS solution has the similar amplitude as our modeled solution, while the SLR solutions have only half of the predicted amplitude. For the annual y component, the SLR solutions have the similar amplitude as the modeled solution, where the GPS solution is a factor of two too larger. The phase differences are within 50 degrees of each other; in particular, the solution of Eanes

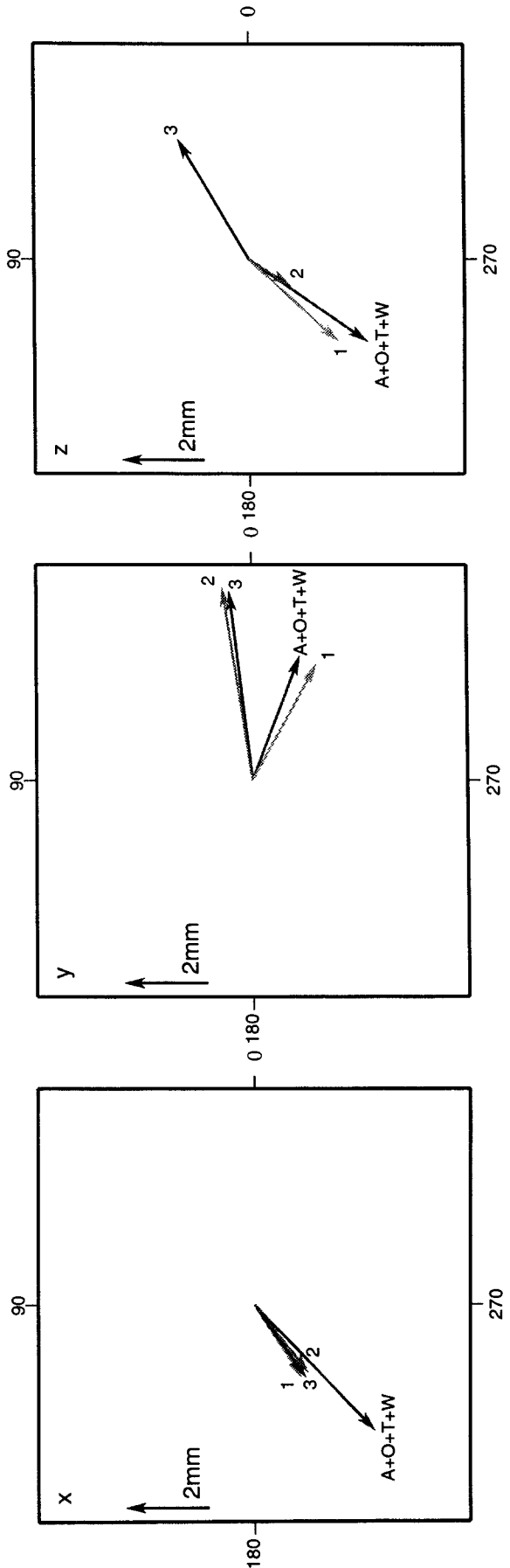


Figure 2: Comparison of the observed and inferred annual geocenter variations.
The notations of A, O, T, W and the phase convention are the same as Figure 1.
The notations of satellite solutions are: 1 LAGEOS I and II combination [Eanes et al., 1998],
2 TOPEX SLR solution [Cheng, 1998], 3 GPS solution scaled by 0.5 [Zhu et al., 1998].

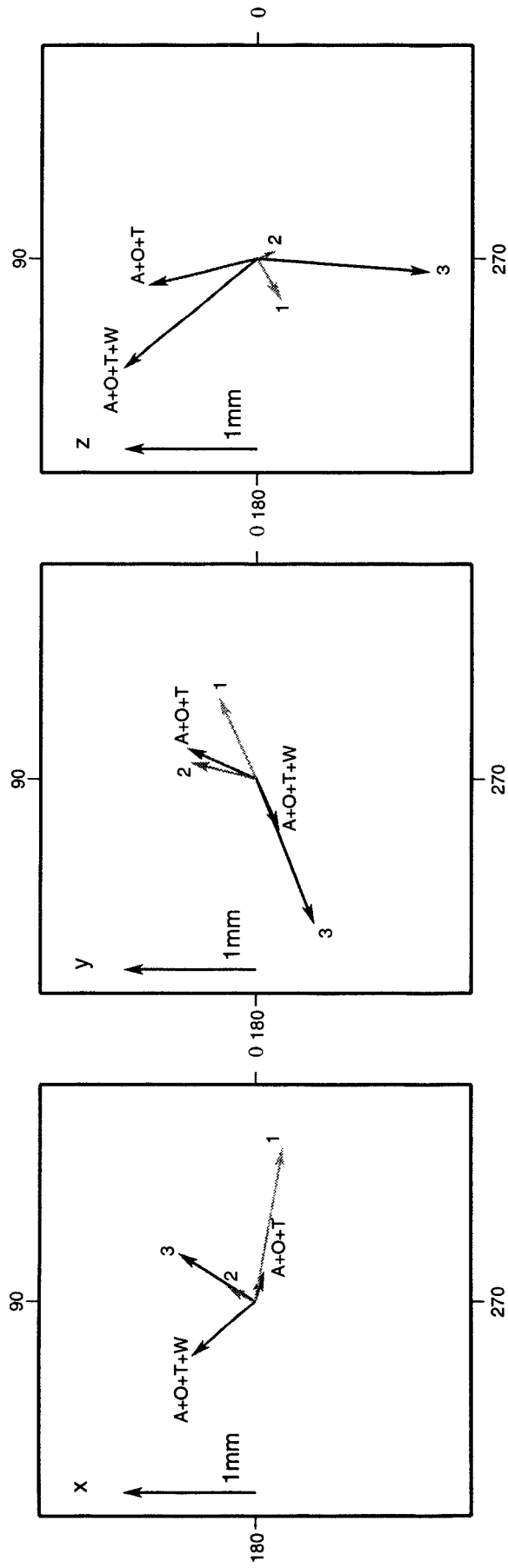


Figure 3: Comparison of the observed and inferred semi-annual geocenter variations. The notations are the same as Figure 2.

et al. [1998] is within 12 degrees of the modeled solution. For the annual z component, the SLR solutions agree in phase with the modeled solution, the solution of *Eanes et al.* [1998] also has good agreement in amplitude with the modeled solution. The GPS solutions are roughly 155° out of phase and a factor of two larger in amplitude with the predicted solution. The agreement of the semiannual components are not as good as the annual components; in particular, we note that the semiannual ground water component degrades the agreement with the model predicted results. We found the similar phenomenon in the comparison between the satellite derived semiannual C_{even} with the model predicted results; adding the ground water contribution degrades the agreement with the model predicted results [*Dong et al.*, 1996]. Such a phenomenon could stem from either the errors in the satellite orbital forcing model, the ground water series or some missing contributions to the semiannual geocenter variations.

3. CONCLUSIONS

Determination of the geocenter variations due to surface mass load from various geophysical sources places constraints on the variations of the origin of terrestrial reference frame and provides a range of the geocenter variation spectrum for space-geodesy. The observed geocenter variations are the lumped sum of multiple contributors. Our results suggest that on the time scale from 30 days to 10 years the primary variability of geocenter variations from atmosphere, ocean and surface ground water occurs on seasonal time scales, which is within 1 cm level. Satellite derived solutions of the seasonal geocenter variations demonstrate good agreement with our model predicted geocenter variations, in particular for the annual components. Such an agreement is encouraging but not yet conclusive. However, at the current stage, the quantitative comparison between satellite derived and the geophysical model predicted geocenter variations is feasible; refined results are expected in the future.

Acknowledgments. We are grateful to M. M. Watkins and R. S. Gross for helpful discussion. The figures were plotted using the Generic Mapping Tools (GMT) software [*Wessel and Smith*, 1995]. The work of DD, JOD and YC was performed at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration (NASA). The work of MKC was supported by NASA under grant No. NAGW-2615 and NAGW-2941.

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Geocenter Estimates from the Global Positioning System

Michael Heflin and Michael Watkins,

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

AGU, San Francisco, December 9, 1997

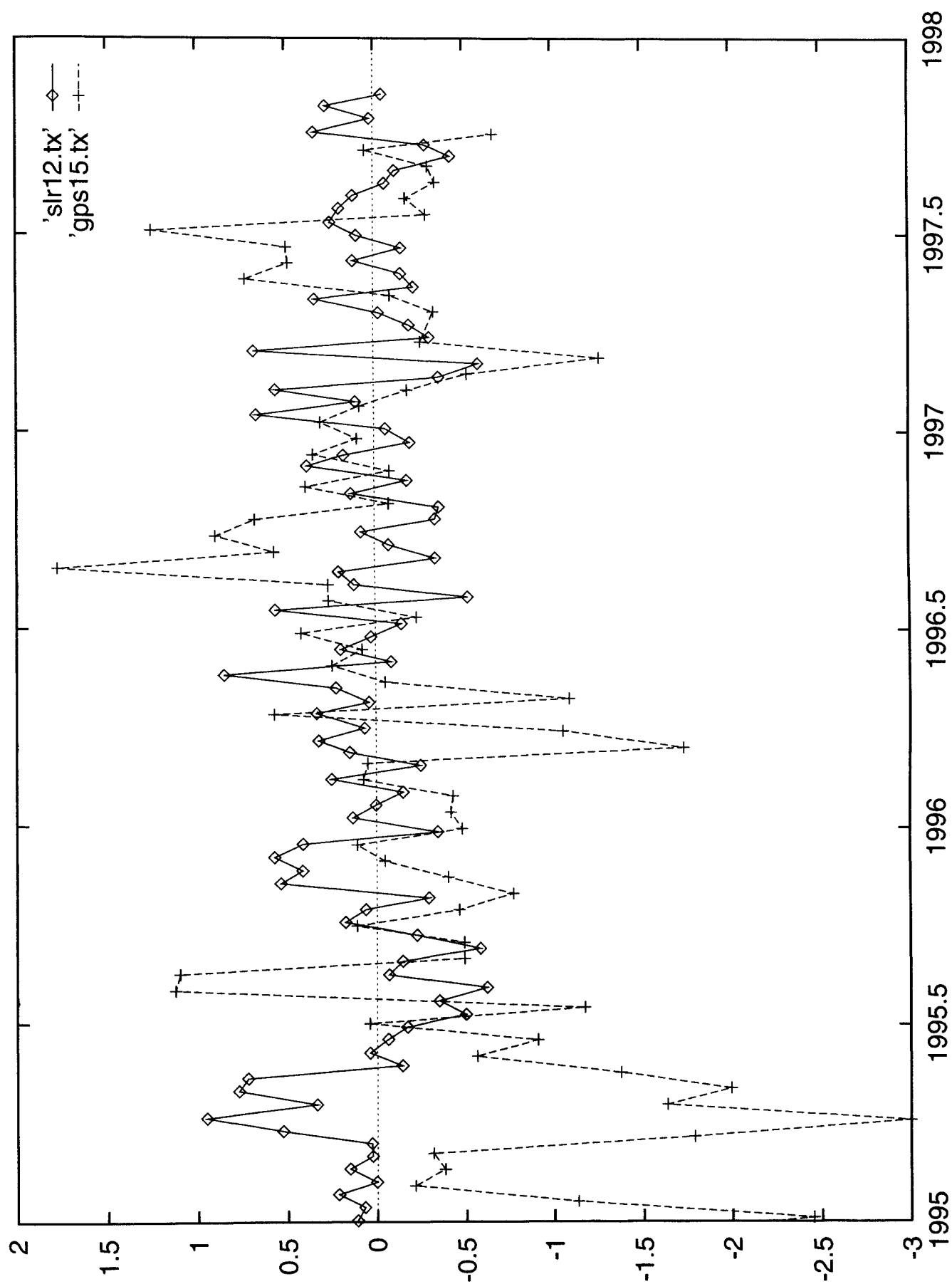
Geocenter Comparisons

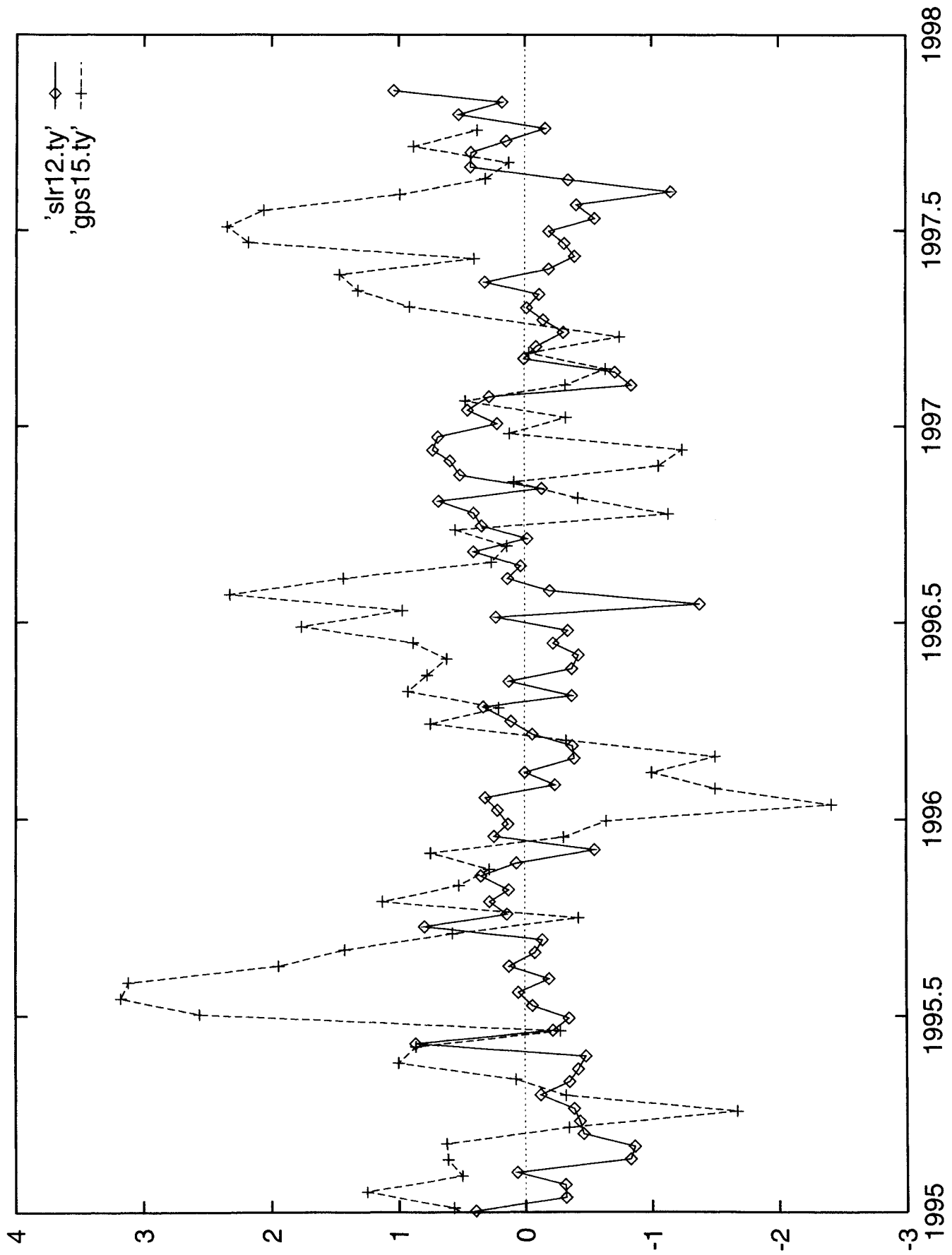
Daily geocenter estimates and scatter of JPL with respect to ITRF94. Origin and scale of ITRF94 from SLR solution SSC(CSR)95L01.

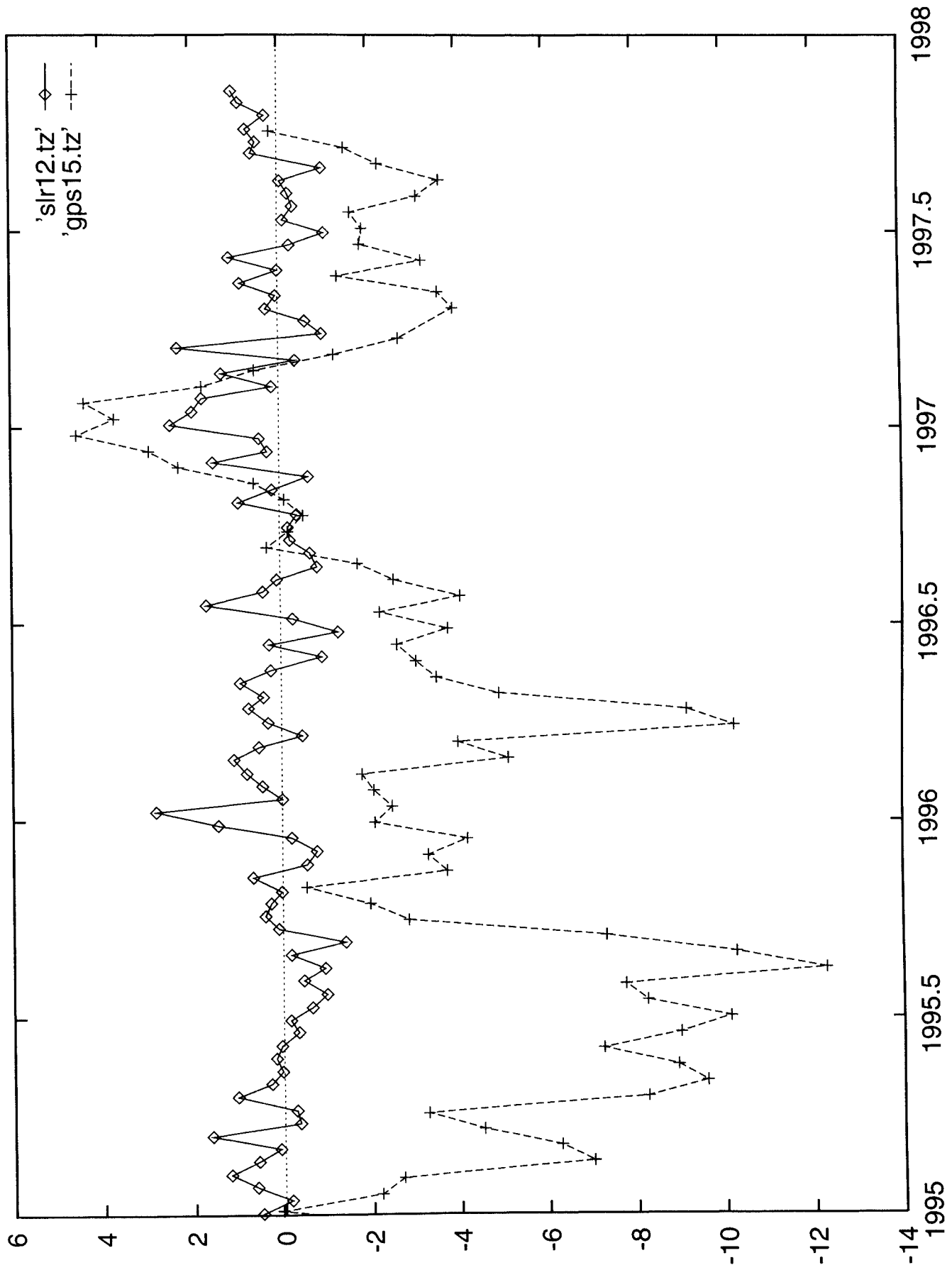
Time	Tx cm	Ty cm	Tz cm	S ppb
Year	-0.1 ± 1.3	0.4 ± 1.3	-0.7 ± 3.1	-2.0 ± 0.5
Month	-0.7 ± 1.2	0.7 ± 1.2	-0.1 ± 1.6	-1.5 ± 0.4

Weekly geocenter offsets and scatter with respect to JPL for one year.

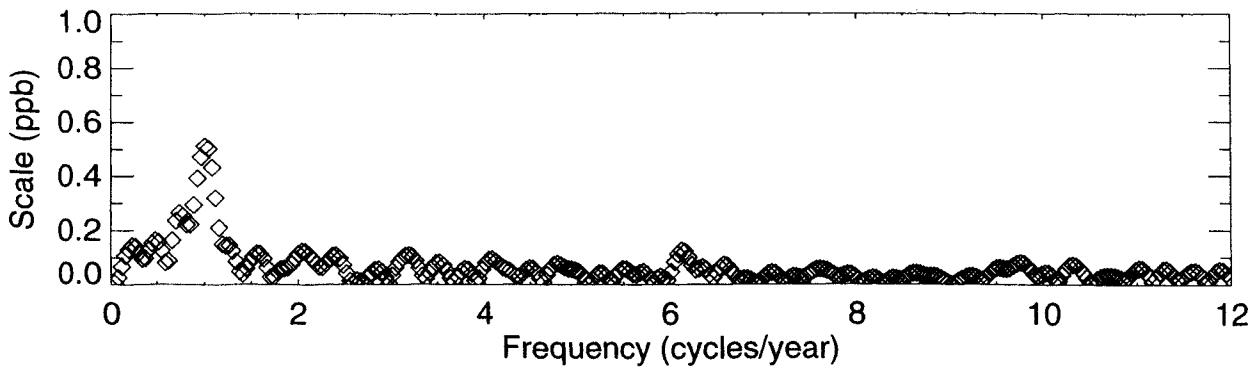
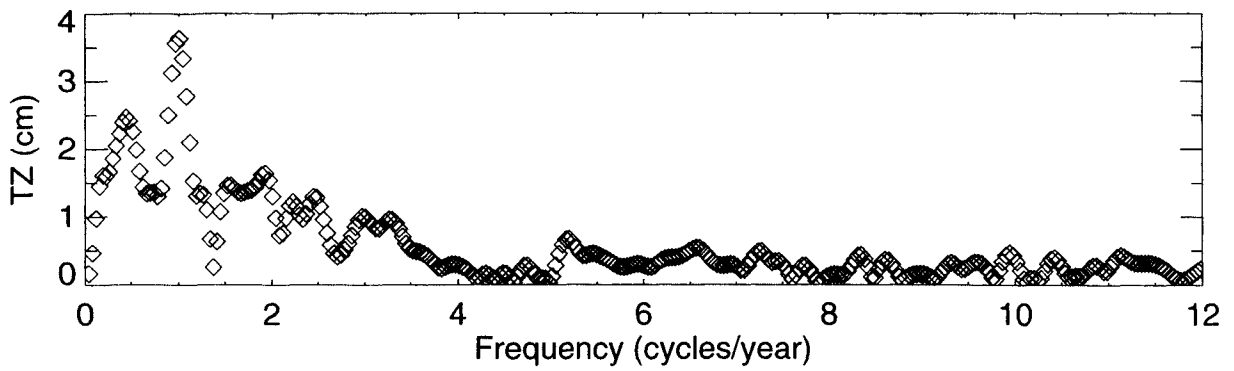
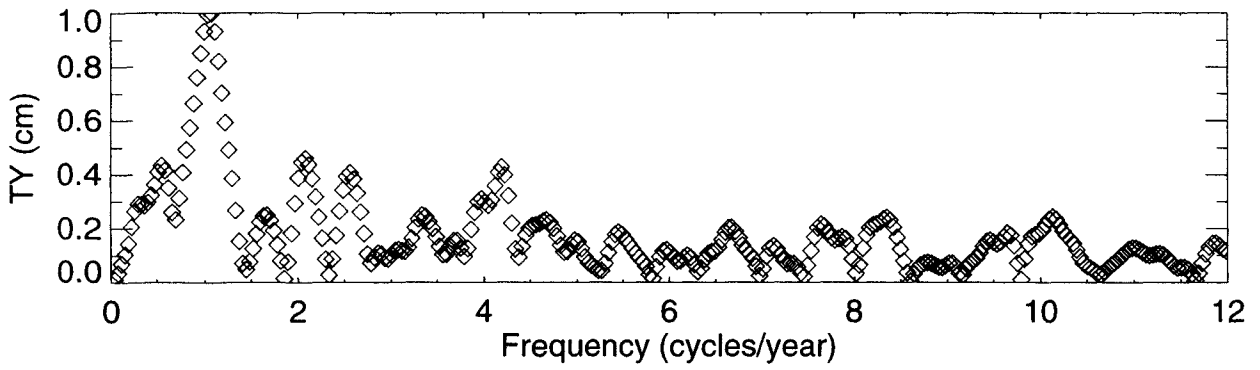
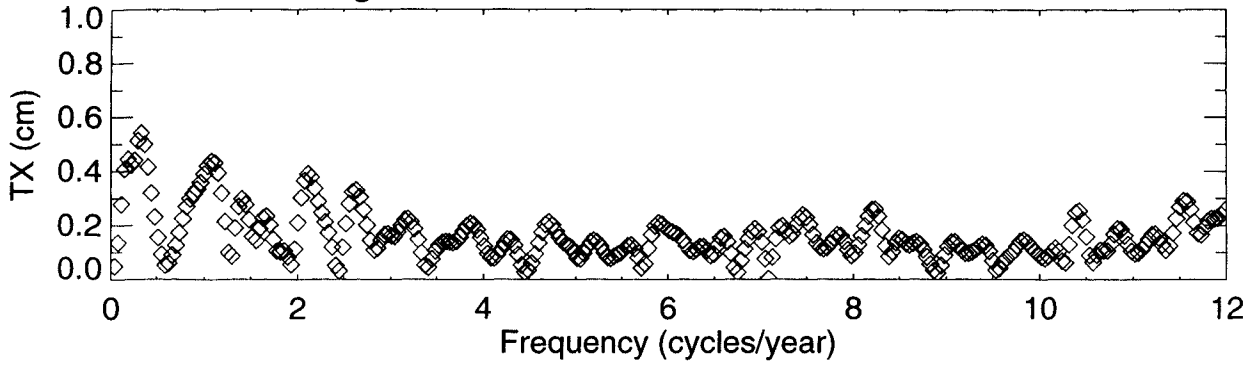
Center	Tx cm	Ty cm	Tz cm	S ppb
COD	1.1 ± 0.8	-0.1 ± 1.1	0.0 ± 2.7	0.0 ± 0.6
EMR	-0.5 ± 1.7	-11.0 ± 2.9	6.9 ± 6.0	-0.4 ± 0.5
ESA	0.5 ± 1.4	1.4 ± 2.8	4.5 ± 6.6	1.4 ± 2.0
GFZ	0.8 ± 1.1	-2.0 ± 6.4	2.3 ± 3.8	0.4 ± 0.4
NGS	0.9 ± 2.1	-19.2 ± 2.7	13.8 ± 6.4	-0.7 ± 1.1
SIO	0.0 ± 1.2	0.1 ± 1.3	6.6 ± 4.9	-0.6 ± 0.8

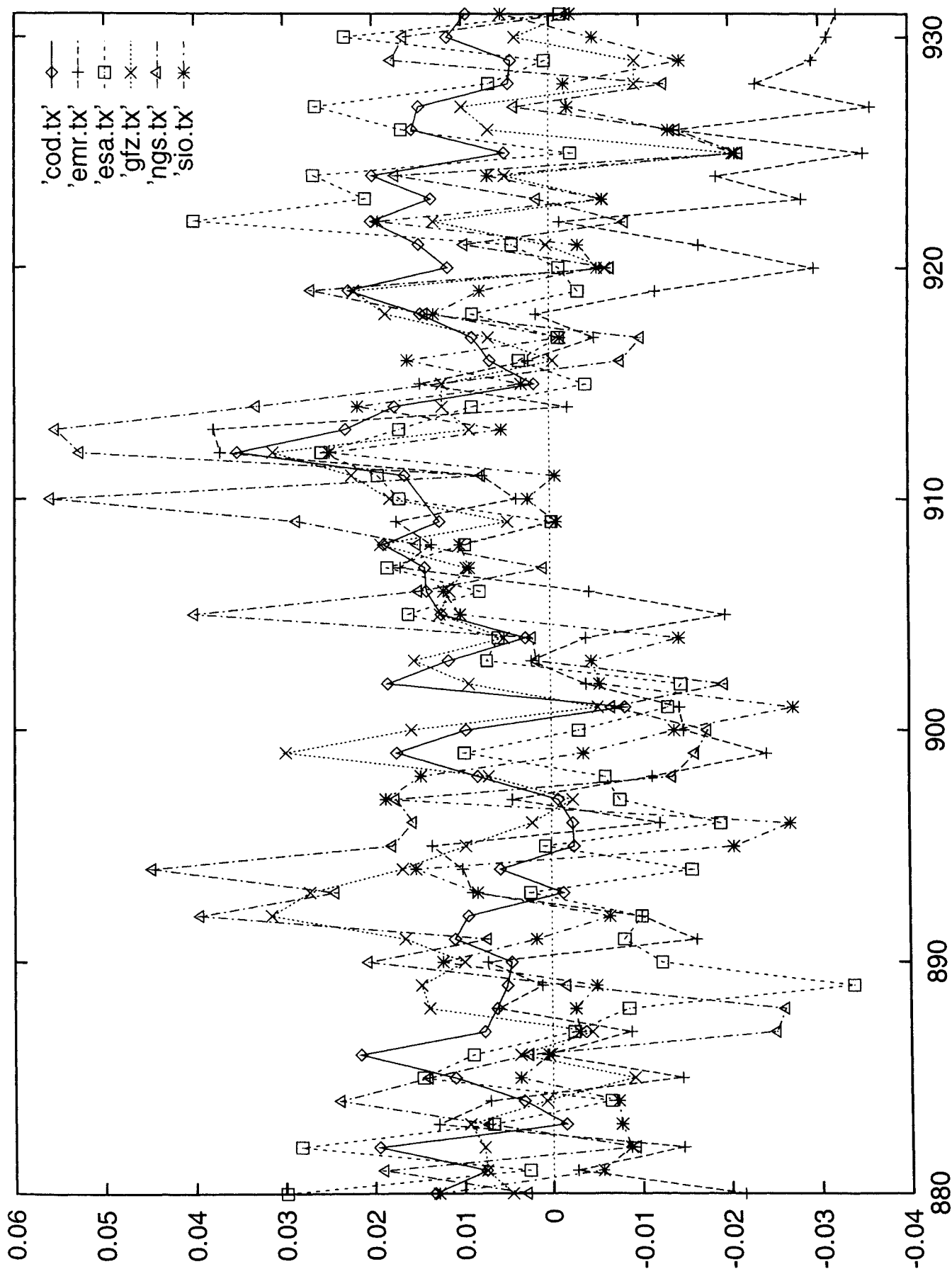


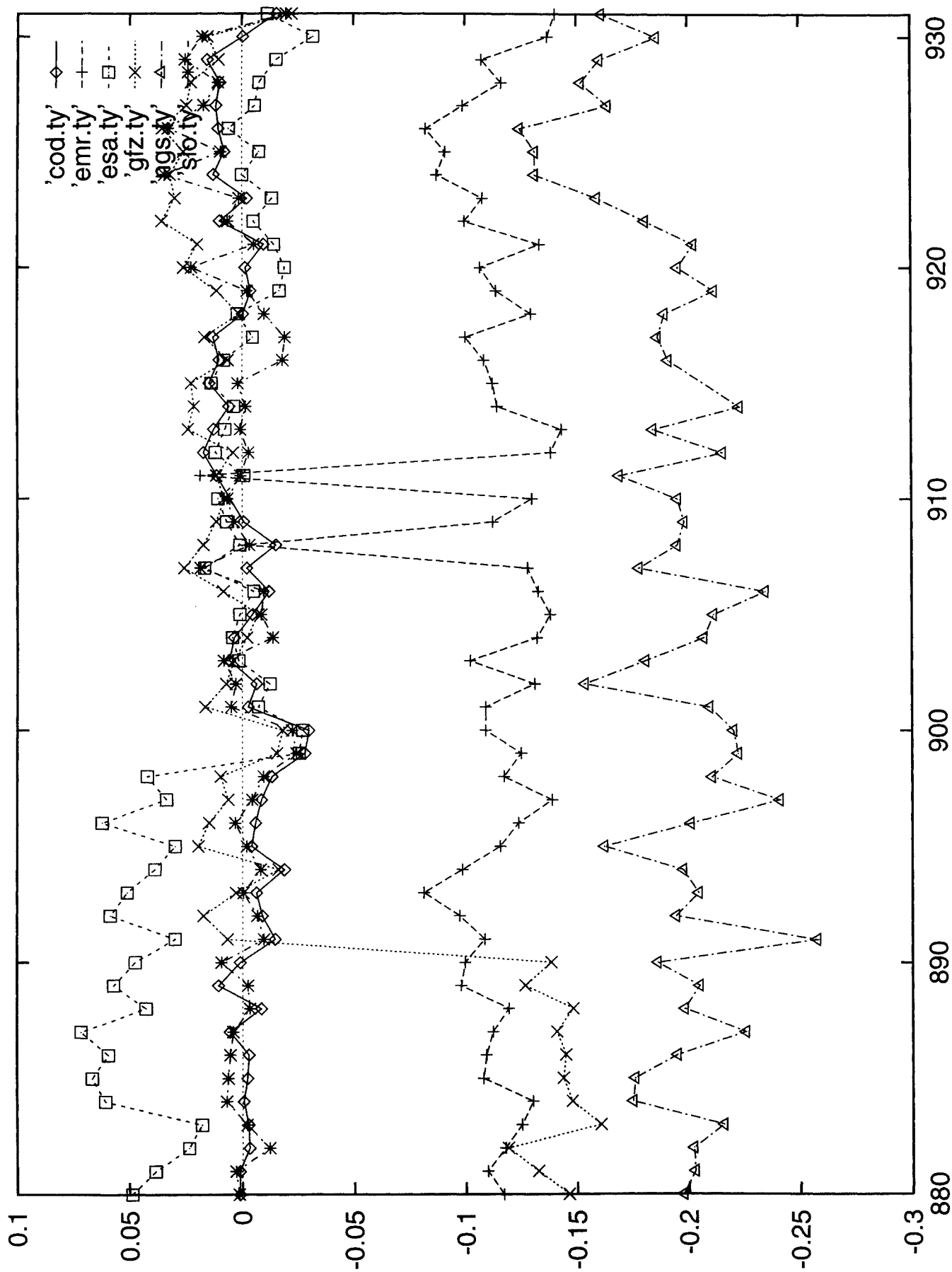


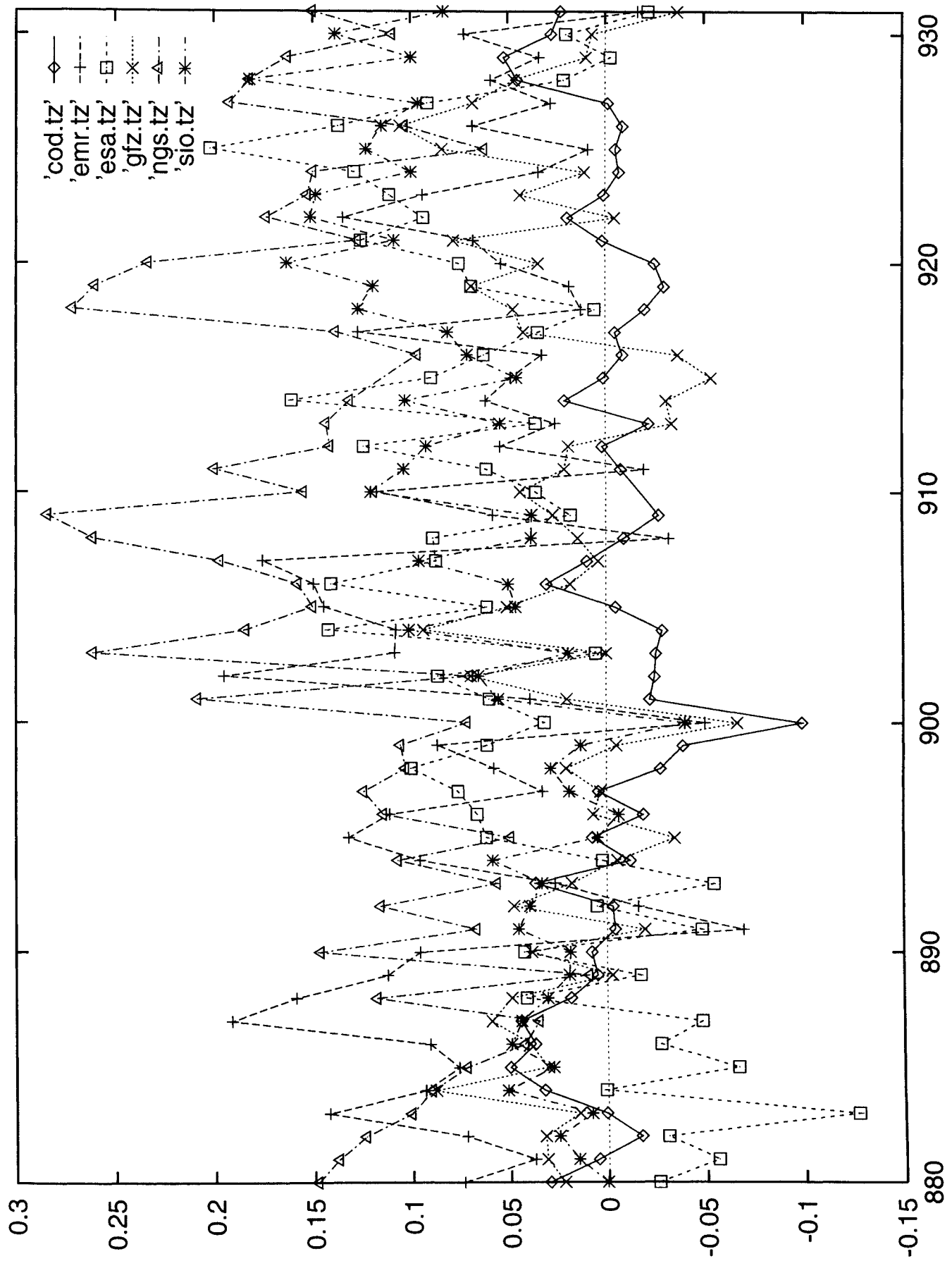


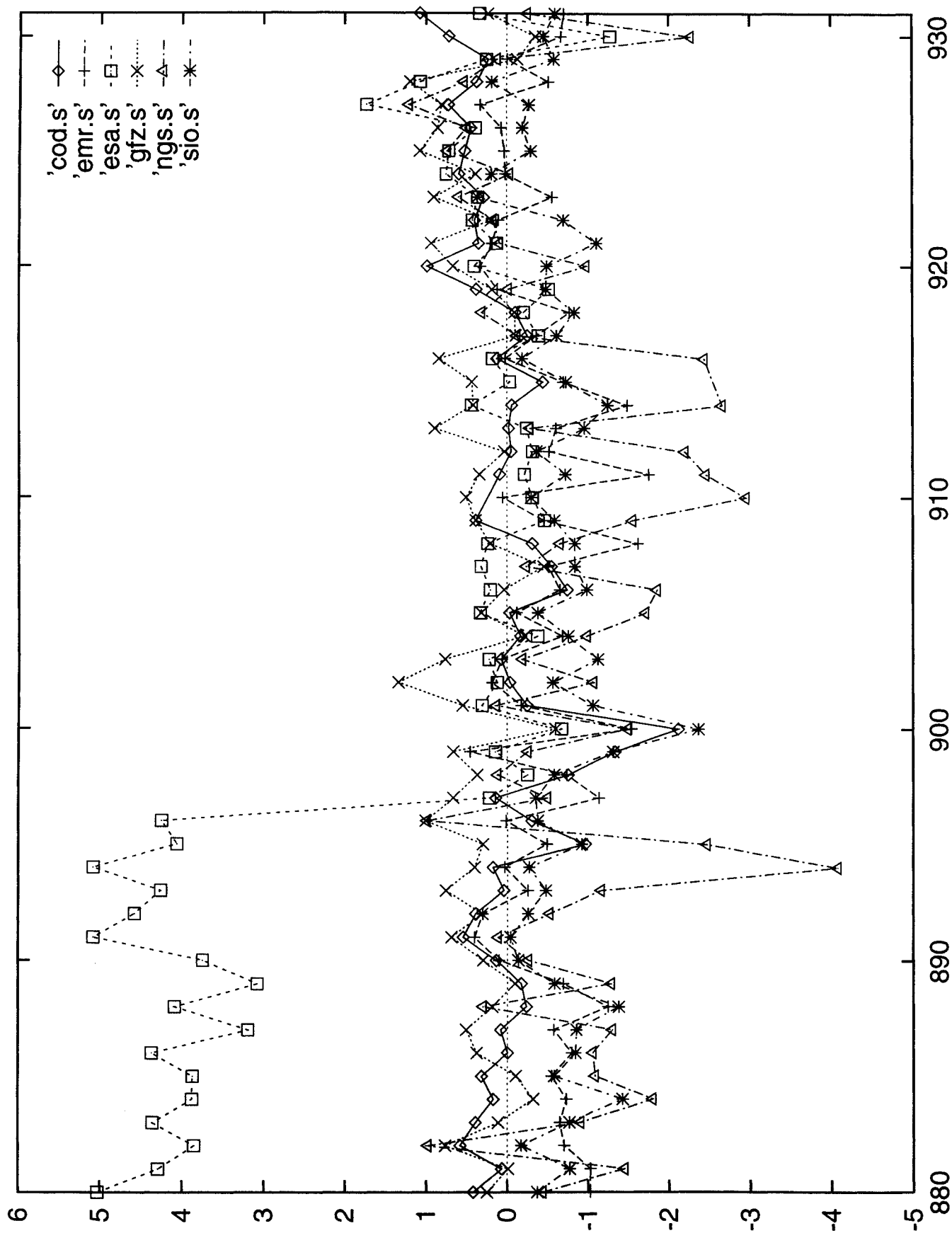
Periodograms for Geocenter and Scale Time Series











Geocenter Motions

Long Period

Secular Rates - Ice Sheet Change and Eustatic Sea Level Rise
Interannual Variations - El Nino and other interannual changes

Seasonal - Atmosphere	2 - 4 mm
Ocean	1 - 3 mm
Ground Water	4 - 5 mm

Dong et al., 1997

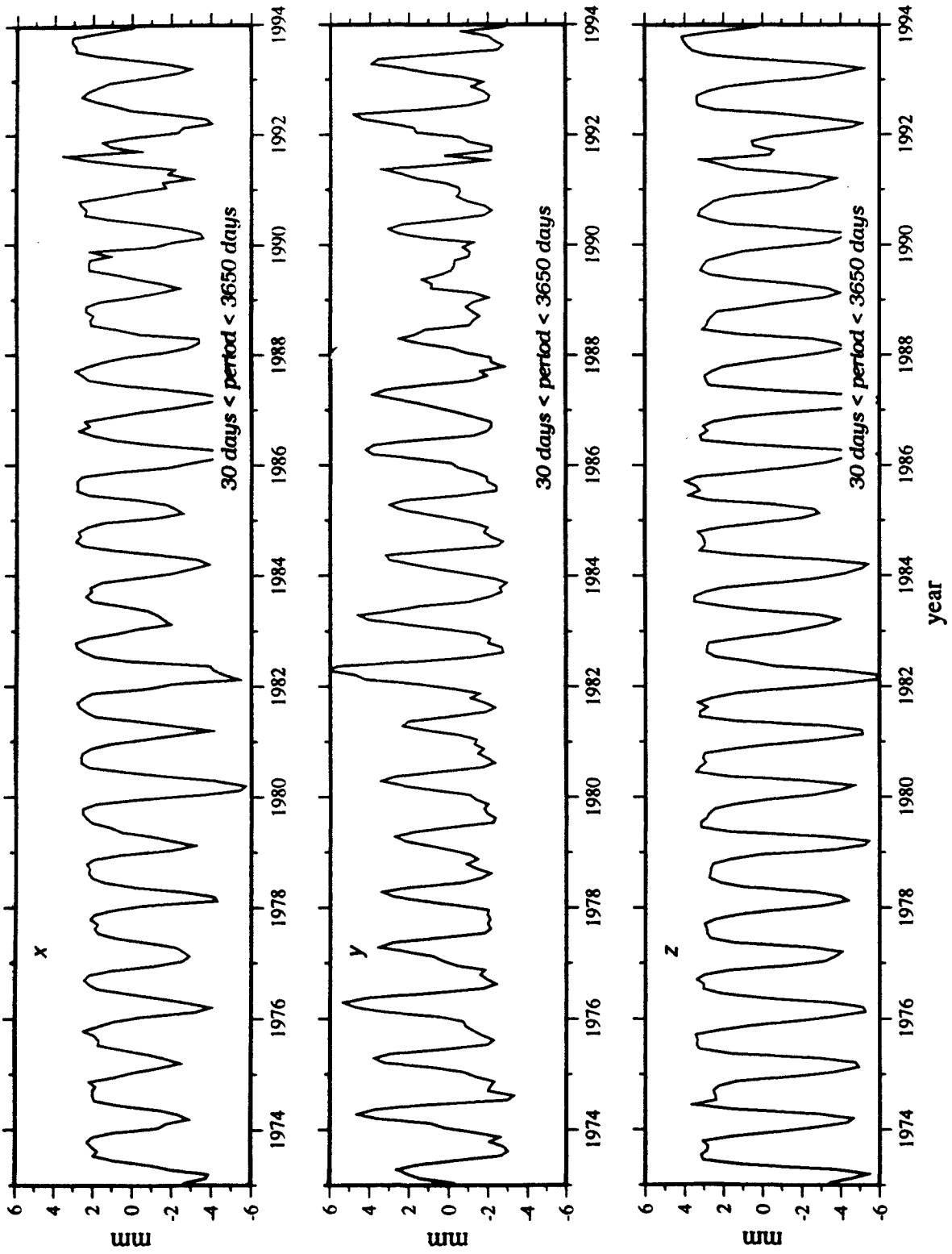
Short Period

Diurnal and Semidiurnal Ocean Tide Response and Forcing 1 - 3 mm

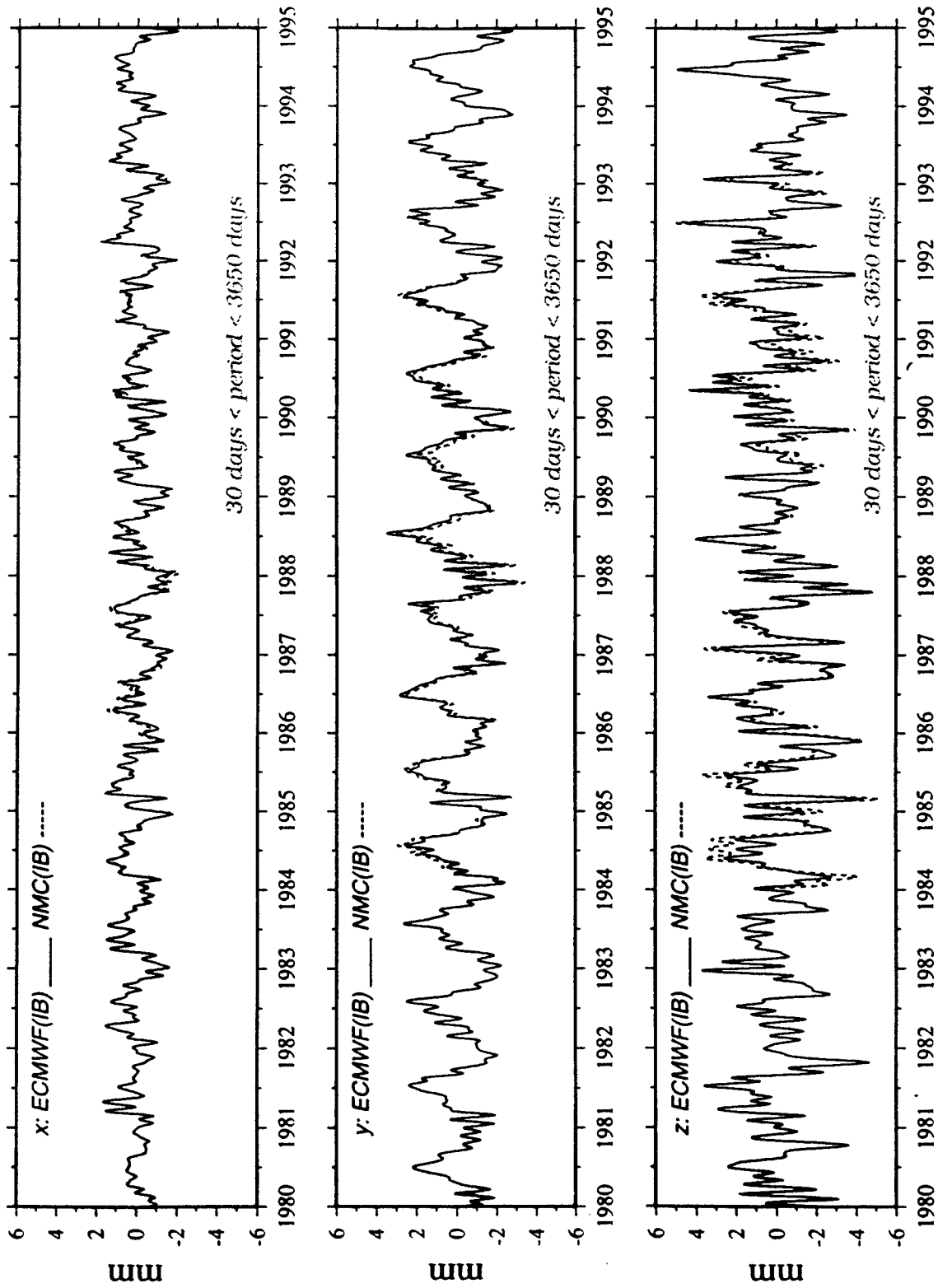
Watkins and Eanes, 1997

GPS Error Sources

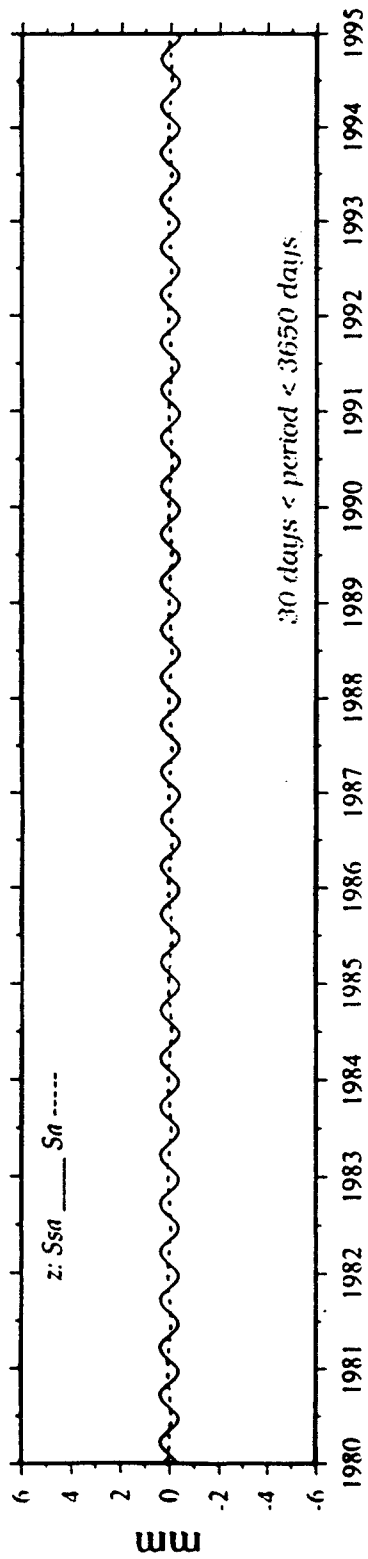
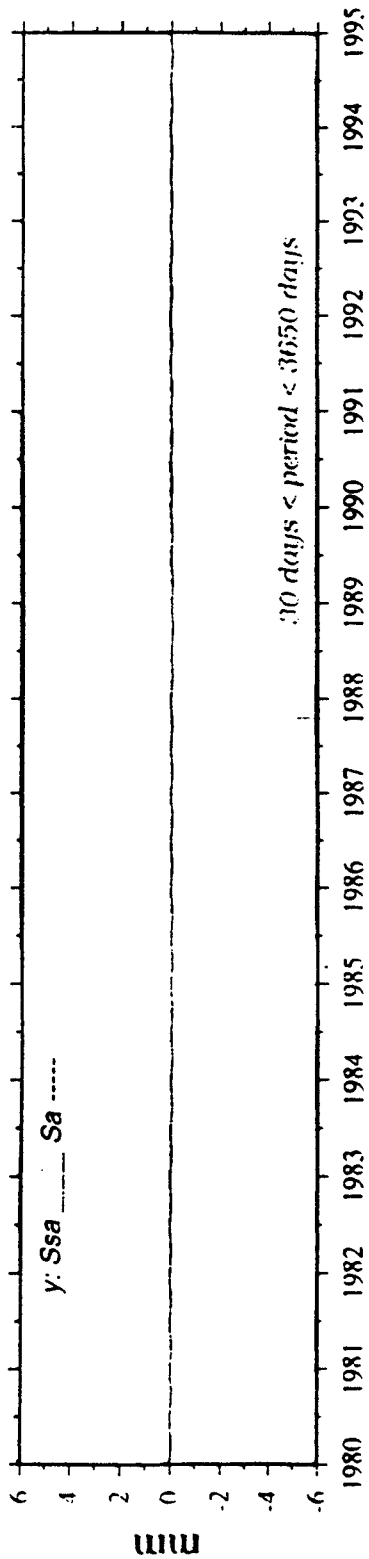
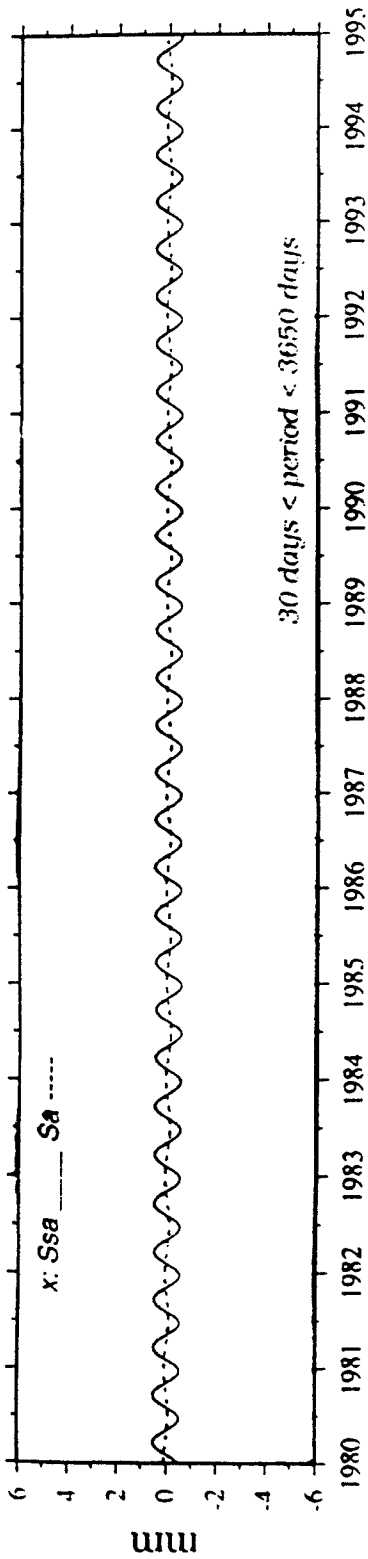
Non-gravitational Satellite Forces - solar radiation pressure
Tropospheric model - asymmetry and mapping function
Antenna Response - phase variations and multipath



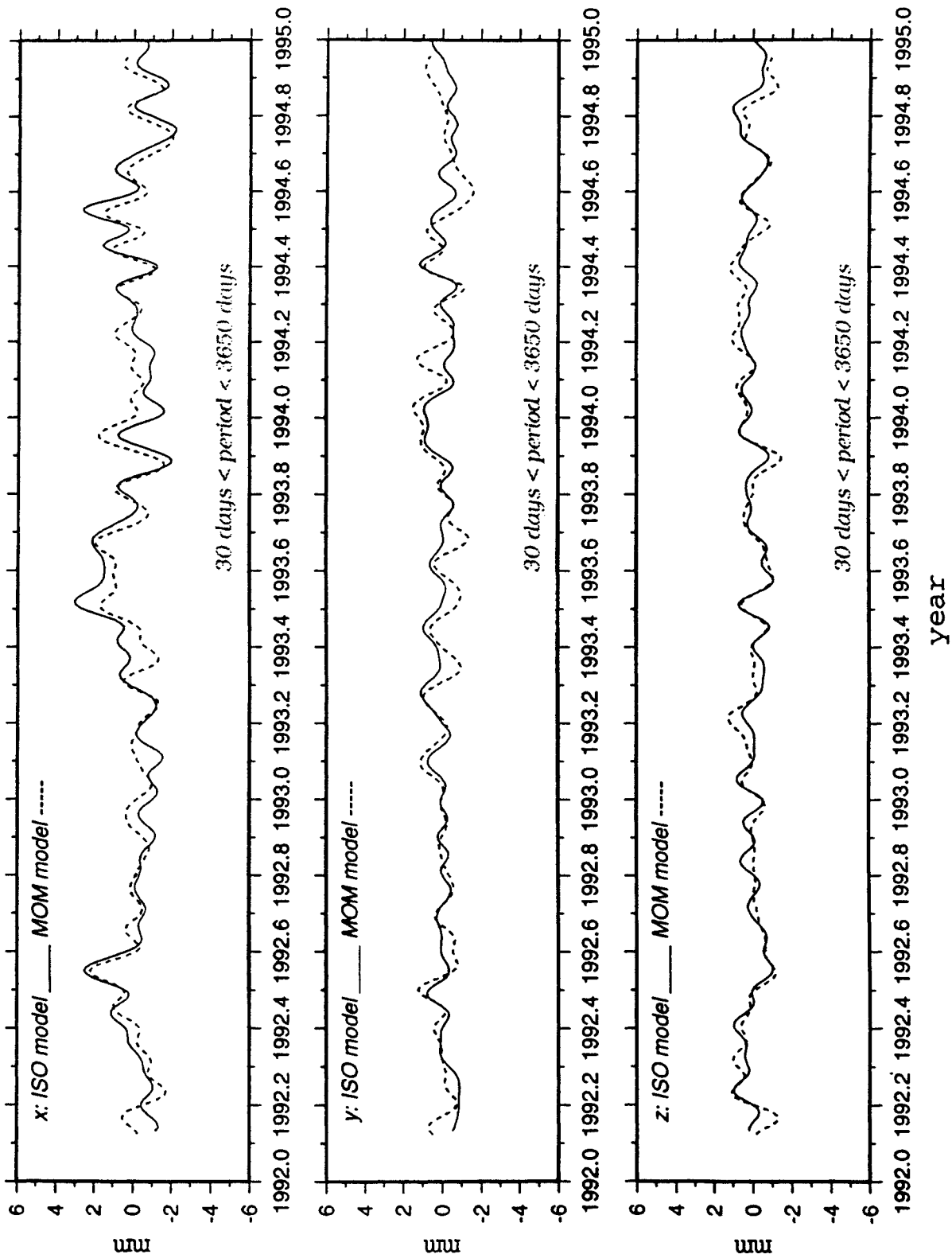
Geocenter variation from groundwater (01/73 - 12/93)



year
Geocenter variation from air mass (01/80 - 12/94)



year
Geocenter variation from ocean tide (01/80 - 12/94)



Summary

Mean agreement 1.1 cm or better in all components for JPL, COD, and SLR.

Recent improvement in geocenter due to global ambiguity resolution.

Recent improvement in scale due to estimation of tropospheric gradients.

Geocenter limited by modeling of non-gravitational satellite forces.

Scale limited by modeling of tropospheric delay and antenna response.

GPS daily geocenter estimates accurate at the 1-2 cm level.

GPS daily scale estimates accurate at the 1-2 ppb level.

GEOCENTER MOTIONS DERIVED BY DIFFERENT SATELLITE METHODS

Horst Montag, Anhalt University of Applied Sciences, Dessau, Germany

ABSTRACT

The gravitational center of the Earth, the geocenter, plays a crucial role as the origin of the terrestrial reference system, and it is also an important parameter for geodynamic investigations. Therefore, it should be determined and monitored with highest accuracy. This can be done by satellite methods using the geocenter as the dynamical origin.

Current accuracies of measurements and modelling allow the study of temporal variations of the geocenter. Comparisons were performed for different solutions based on Satellite Laser Ranging (SLR), Global Positioning System (GPS) and Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) data. Although the potential of the methods treated is different to prove the motion of the geocenter the results demonstrate significant variations of all three Cartesian components, mainly seasonal effects. The amplitudes are in the order of several millimeters; the phases show partly large differences. Conclusions for further activities are drawn based on these comparisons.

INTRODUCTION

The geocenter realized by the coordinates of the tracking network on the solid Earth, is used as the origin of the Terrestrial Reference System (TRF). For the geodesy this geocentric coordinate system plays a crucial role as the absolute system. Therefore, it should be determined and monitored with highest accuracy.

Physically, the geocenter is defined as the center of the mass distribution of the entire Earth interior, the oceans, and the atmosphere; it is the dynamic origin of satellite motion. Caused by a great variety of inner and outer forces on the Earth system this center of mass is changing. Setting equal zero the degree one Stokes coefficients of the Earth's gravity field the motion of the geocenter is equal to the translation of the origin of the used TRF, that means the relative motion of the gravitational center of the Earth with respect to the tracking network.

Current accuracies of the different methods allow to investigate the temporal variations of the geocenter. With reference to the more detailed paper delivered to the Fall 1997 AGU Meeting (Montag, 1997) this brief report is intended to evaluate the significance of the observed phenomena on the basis of the comparison of the results of different satellite geodesy solutions.

COMPARISON OF THE DIFFERENT SOLUTIONS

Based on the data of the last years (time span between 3 and 5 years) the geocenter solutions used consist of the following:

- three solutions using Satellite Laser Ranging (SLR) data to the satellites Lageos 1 and 2 (Montag et al., 1996; Eanes, 1997; Pavlis, E., 1997),
- one SLR solution with Topex-Poseidon (T.-P.) satellite (Cheng, 1997),

IERS(1998) Technical Note No 25.

- three GPS data solutions (Montag et al., 1996; Zhu, 1997; Heflin, 1997) and
- one solution using DORIS data on SPOT2, SPOT3 and Topex-Poseidon satellites (Bouille and Cazenave, 1997).

Different software packages were used for the different analyses. The model parameters generally conform to the IERS conventions (McCarthy et al., 1996), but several exceptions refer to the Earth gravity field, the tidal parameters and others. Also, the kind of parameters and the parameter estimation procedure differ between the different solutions. Here the Lageos solutions have advantages because of the smaller orbital perturbations. In the case of GPS, e.g., the estimation of the solar radiation (once per revolution, as velocity impulse or others) or the kind of phase ambiguities solutions can have essential influences although the solution of both effects have been lately steadily improved.

Generally, the different solutions are more or less sensitive to the model parameters and the estimation procedure. This may cause systematic errors which are always difficult to estimate. Therefore, the redundancy of different methods is important. The best procedure is to combine the different solutions in a proper way.

The comparisons have shown that the precision of the obtained components of the geocenter motions (scatter about their respective means) is generally significantly better for x and y (about or less than 5 mm) than for the z component, which is partly more than 10 mm. But there are several deviations. In the case of the GPS solutions the scattering is much higher. The Topex-Poseidon solution (SLR) show a different behavior. Here the z- component is more smoothed than x and y; for x and y the precision is in the same order as for the other solutions.

In their general course, the variations of the three Cartesian geocentric parameters are interpreted as geocenter motions. They show a different behavior, as for the amplitude as concerning the phases. The solutions based on Lageos vary between about +10 mm and -10 mm for x and y; z reaches amplitudes of more than 20 mm. The GPS solutions show partly much higher amplitudes, especially again for z. Similar big variations show the differences of the weekly station coordinates solutions of the seven IGS Analysis Centers (CODE, EMR, ESA, GFZ, JPL, NGS, SIO) with respect to ITRF94 performed by JPL, MIT and NCL (30 weekly results in 1997/98, Kouba, 1997). This confirms the relatively large sensitivity of the modelling procedure (which is partly different in the mentioned Analysis Centers) to the GPS data. The geocenter variations based on DORIS data and Topex-Poseidon analyses amount about or less than 20 mm (between ± 10 mm) for all three components.

DETERMINATION OF THE ANNUAL AND SEMIANNUAL GEOCENTER VARIATIONS

The results of the Fourier power spectra analyses for the time series of the geocenter variations show an annual period for all components and all solutions. The derived periods amount to between 220^{d} and 380^{d} . This is mainly caused by the seasonal mass redistributions, but other phenomena, e.g. longer and long-term climate oscillations or long-periodic tides and nutation effects, have some influence too.

A semiannual period seems to be significant also but it was not found in all series (partly GPS and T.-P.). The derived period lengths vary between 120^{d} and 210^{d} .

Additionally, several other periods were found, but not the same in all series and partly not very significant. Mainly, they are situated in the region of a fortnight (only higher resolved GPS solution) and of two to four months. Some series indicate periods of about two years too. For investigating the shorter periods one needs a higher resolution, and for longer periods the time series should be prolonged.

For the annual and semiannual variations of the geocenter the amplitudes and phases (referred

to 1994.0) were determined. Generally, the amplitudes of the annual period are bigger by a factor of 2 to 3 than the semiannual effects, but the differences between the single solutions are relatively high. Especially the GPS solutions delivered unrealistic results in some cases. The derived precision indicate uncertainties up to several mm for the amplitudes; for the phases the errors can reach very large amounts depending on the amplitude and the method. These precisions plus estimated values for systematic effects were used to calculate the weights of the different solutions. The weights for a single solution and component vary between 1 and 8. Because of unrealistic results, a single GPS solution was not included in further averaging (weight 0). Thus the contribution of the Lageos solutions amounts more than 50%, those of Topex-Poseidon plus Doris about 30%, and that of GPS about 20%.

Using these weights the overall means were computed and are shown in Table 1. Both the x- and y- component have an amplitude for the annual period of about 3 mm, but a phase difference of about 100° . The errors (weighted r.m.s.) are in the order of $\pm 1\text{ mm}$ and $\pm 20^\circ$, respectively. The annual amplitude for z is 4.5 mm with an uncertainty of $\pm 1.7\text{ mm}$. The bigger amplitude for z may be caused by the dominance of seasonal mass redistributions between the northern and southern hemisphere. The higher errors (amplitude and phase) are, as for the investigation of other phenomena, at least partly related to the geometry of the tracking station network. The phase for z amounts 87° and is situated nearly in the middle between those of the x- and the y-component.

The amplitudes of the semiannual periods are about half of the annual amplitudes in the case of x and y; for z the difference is even bigger. Again the phases are different for all three components.

Table 1: Summary of Annual and Semiannual Geocenter Motion (weighted means)

Component	Annual		Semiannual	
	Amplitude [mm]	Phase $[\circ]$	Amplitude [mm]	Phase $[\circ]$
1	2	3	4	5
x	2.9 ± 1.0	32 ± 18	1.4 ± 0.3	190 ± 30
y	3.7 ± 1.3	146 ± 18	2.0 ± 1.2	273 ± 26
z	4.5 ± 1.7	87 ± 22	1.0 ± 0.6	74 ± 27

The phase differences reflect the difference of the effect of the mass redistributions in time and space. Recent investigations about the influence of atmosphere, ocean and groundwater (Dong et al., 1997) have shown similar amplitudes. That means the amplitudes of Table 1 can be, in general, quite well explained by these phenomena. But this is not the case for the phases; here a fairly good correlation can only be seen between the ground water effect (the biggest influence) and the z-component of the annual variation.

CONCLUSIONS

The comparison of the above solutions for the investigation of geocenter variations based on different data and different software systems has shown that this effect is real. Although the potential of the applied methods for the evidence of the geocenter behavior is different, common signals demonstrate the components of the geocenter variations. In future

the proof of the geocenter motion has to be further improved by including more and prolonged observation series, and by using more expanded and sophisticated parameter sets. The SLR solutions with Lageos will continue to provide the basic elements of the determination of geocenter motions.

The most significant effects are the annual and semiannual geocenter variations caused by the different seasonal mass redistributions in the Earth system (air pressure, ocean circulations, ground water, snow etc.) superimposed by other phenomena (longer periodic climate oscillations, tides, nutation; convections, core-mantle interactions and other mass motions in the Earth interior). Thus the observed time series of geocenter variations can be used to constrain geophysical models. Therefore, the inter-disciplinary investigation of the geocenter motion and its correlation with the different geodynamic phenomena will become more and more important for future analyses.

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FORTNIGHTLY RESOLUTION GEOCENTER SERIES: A COMBINED ANALYSIS OF LAGEOS 1 AND 2 SLR DATA (1993-96)

E. C. Pavlis, JCET/UMBC and NASA Goddard SFC

INTRODUCTION

This contribution presents the results of a combined analysis of satellite laser ranging (SLR) data from LAGEOS 1 and 2 for the determination of a high resolution (15-day) series of the so-called “center of mass motion”. The interval spanned by the data covers from 1993 until the end of 1996. We conclude that the SLR technique, being currently the most accurate one to determine absolutely the location of the tracking stations with respect to Earth’s center of mass about which the tracked satellites are orbiting, is also the best one to monitor the motion of the geocenter. The formal accuracy for the equatorial components X and Y are 1.3 mm and for Z 4 mm. The scatter of the three however is more indicative of the reliability of the series and suggests 3 mm and 11 mm respectively.

GEOCENTER MOTION

SLR, amongst a number of space techniques, provides the most accurate absolute positioning with respect to the geocenter. This is realized through the dynamics governing the motion of the satellite targets about the point which they orbit: the instantaneous center of mass of the planet. We gain access to this point through the coordinates of the tracking sites that we determine from our data. Viewing Earth as a three-part system: the atmosphere, the oceans, and the solid earth, all three undergo mass redistribution, each part with characteristically different time scales. Some of these, from the better to the less well understood, are due to: tides, oceanic and atmospheric circulation, loading, convection, etc. .

The level of accuracy required by IERS in the definition of the geocenter necessitates that we recognize and account for motions that result from a constant redistribution of the terrestrial masses caused by these phenomena in the terrestrial environment. This manifests itself as a continuous motion of the geocenter with respect to the crust-fixed tracking network, albeit only by a few millimeters or so. What we are then really interested in determining is the “trajectory” of the geocenter relative to some conventional origin. The lack of a known law that governs this motion limits us to the solution of a discrete problem where we define an average geocenter over short time intervals the length of which depends on the accuracy, resolution and data availability of the utilized technique.

The ideal method would employ SLR from a well-distributed global network with enough LAGEOS-type targets to solve for one set of station coordinates on a daily basis (or even more frequently). In practice only GPS has such a global network and abundance of data to afford such frequent solutions. Unfortunately though, GPS lacks the inherently high accuracy and unambiguous nature of SLR and it will take additional modeling development until it can contribute daily at the few millimeter accuracy level. The SLR results presented here are based on 15-day solutions for the average geocenter location, though in recent years, due to the network expansion even finer resolution is possible.

APPROACH

Cartesian coordinate offsets from a conventional origin are intuitively the simplest although not the only way to visualize and describe the motion of the geocenter. As reference, we could choose a long term average from the analysis of several years of SLR tracking data.

On the other hand, since the model describing the geopotential depends on the adopted coordinate system, any changes in the definition of that system introduce changes in the parameters describing the geopotential as well. These are time-dependent changes and for the most part, they affect the lower degree and order terms, [Heiskanen and Moritz, 1967]. In that respect, every one of the seven parameters describing a similarity transformation between two Cartesian coordinate systems has a corresponding parameter in spherical harmonic space, the most common representation for the geopotential in geodetic computations.

This sensitivity provides for an alternate but equivalent way of describing the motion of the geocenter: a series of the three harmonics that correspond to the linear origin offsets ΔX , ΔY , ΔZ . These are $C_{1,1}$, $S_{1,1}$ and $C_{1,0}$ respectively. The exact relationship between the two sets of parameters is as follows (*ibid.*):

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

where $C_{0,0}=1$. This relationship can be used to transform such estimates between systems for comparison purposes. To distinguish between the two, we call the Cartesian offsets derived from coordinate solutions the “geometric” method, while the offsets obtained from the gravitational harmonics’ changes the “dynamic” method.

The geometric method is more sensitive to the tracking network configuration variations between averaging intervals, while the dynamic one smoothes over such variations using the orbit as a filter. This peculiarity in the sensitivity of each technique introduces slight differences in the derived estimates which however are below their formal accuracy. Although we will show these differences, we will concentrate our evaluation of the results on the dynamic method. All accuracy estimates we quote are 3σ values scaled so that $\chi^2=1$.

MODELING

The analysis of SLR data requires numerous and elaborate models describing the forces acting on the satellite, the observing station, and the medium that separates the two. Most of these models are continuously revised and improved, the community however strives to follow the adopted “conventions” to facilitate comparisons of results. In our analysis we have followed with only a few exceptions (which we explain here), the “IERS Conventions (1996)”, [McCarthy, 1996].

The deviation of our modeling from the conventions is restricted to the use of the EGM96 static and tidal gravity model [Lemoine et al., 1997] and the use of the older Solar and Planetary Ephemeris DE-200 instead of the more recent DE-403. With regards to the second, we should clarify that despite the use of DE-200 for third body ephemerides, the new nutation model was used, as it is required by the Conventions.

The use of the more recent gravity model was warranted in order that we obtain the highest quality of orbits possible. EGM96 is far superior to its predecessors and above all, its static and tidal components have been developed simultaneously, assuring full compatibility in describing the instantaneous total potential acting on a satellite.

The data were analyzed in 15 day batches, each batch forming one arc with a single set of initial conditions that were fit to the data in a least squares adjustment. In addition to the initial conditions, we adjusted a set of ad hoc accelerations: a Fourier pair at the orbital frequency for each satellite in the along-track and in the cross-track direction, and constant acceleration in the

along-track direction. A new set of such accelerations were adjusted every 5 days (i.e. three sets per arc). The solar radiation pressure coefficient was constrained for both satellites at the nominal values of 1.13 and 1.14. Earth albedo and anisotropic thermal effects were modeled for both LAGEOS 1 and 2 [Rubincam, 1988, 1990], [Rubincam and Mallama, 1995], [Martin and Rubincam, 1996] and [Rubincam et al., 1997]. The orientation of the satellite spin axis, required in modeling thermal effects, was obtained from the model described in [Farinella et al., 1996]. In addition to the terrestrial and lunisolar perturbations, we have modeled those arising from the planets Mercury, Venus, Mars, Jupiter, Saturn, Uranus and Neptune. The metric used in the formulation of the equations of motion and the observer-dependent data corrections was that of Einstein's theory of general relativity (according to the Conventions).

The Terrestrial Reference Frame (TRF) origin was described by the tracking station coordinates with *a priori* values from GSFC's SSC/SSV 96L02 [IERS, 1997]. All station positions were adjusted with the exception of a set of minimal constraints to remove the usual singularities. In particular, the latitude and longitude of one site (Greenbelt, Maryland) and the latitude of an additional site (Maui, Hawaii) were kept fixed to *a priori* values. The evolution of the network due to tectonic motions at the sites was described by the adopted velocity model. Even though SLR is a primary system in determining such motions, the length of the analyzed data set (only four years) was deemed inadequate to reliably resolve these motions at all sites. The *a priori* orientation of the reference frame was described by the Earth orientation series SPACE96, [Gross, 1996]. Our analysis adjusted daily for the two components that describe the orientation of the instantaneous rotational axis with respect to the TRF (polar motion) and the excess length of day.

The sites' displacement due to ocean loading effects was modeled with the coefficients provided by H.-G. Scherneck (HGS) according to the IERS Conventions. Another effect of the ocean tides that has become an important source of variance in the definition of the TRF is their influence on Earth orientation and the geocenter itself. Estimates of these effects on the basis of SLR data were reported already in [Pavlis and Rowlands, 1993] and [Pavlis, 1994], and there have been numerous other models developed using other techniques (VLBI, GPS), or based on theory and some of the recently developed ocean tide models. In particular, we used the ocean loading set from HGS that includes implicitly the correction due to the tide-induced motions of the geocenter at the diurnal and semi-diurnal frequencies, derived on the basis of the CSR3.0 ocean tides. Similarly, for the corrections of tidal origin in polar motion and Earth rotation at the diurnal and semi-diurnal frequencies we used the IERS Conventions model of R. Ray.

In addition to applying known data biases, we allowed for measurement bases for all stations, solving for them in the final stage on a per site mode, based on the tracking of both satellite targets. This characterizes them as a "site" rather than a "target" parameter, which is more appropriate for the case of identical satellites. The estimation of these biases becomes also more robust due to the increased amount of data and tracking geometry.

Finally, the last set of parameters allowed to adjust are the low degree and order harmonic coefficients that describe the time dependence induced in the gravitational model due to mass redistribution of other than tidal origin. Rotational deformation induced changes in the second degree - order one harmonics were modeled according to our extended model accounting for secular wandering of the mean pole [Marsh et al., 1988]. Post-glacial relaxation effects on the second zonal harmonic J_2 were modeled as a secular rate at the value used in the development of EGM96.

RESULTS

The results of primary interest to the IERS geocenter campaign are the series of biweekly average position of the geocenter with respect to the conventional origin defined through the adopted network site positions and velocities. As we already discussed this in a previous section, we derived these series in two different but equivalent ways. The series that

are illustrated in Figure 1 are the result of the “dynamic” approach. It is quite evident that the magnitude of the variation for the equatorial components ΔX and ΔY , and that of the axial component ΔZ is markedly different. The reason behind this of course is the fact that Earth rotation efficiently averages signals sectorially, never allowing for the build-up of large signals, while the much slower seasonal changes produce much more significant variations between northern and southern hemispheres. This disparity between components was detected by all of the participating techniques in this campaign.

The statistics for each of the two approaches as well as their differences are given in Tables 1 through 3. The expected high degree of agreement between the two series is obvious. It is however stressed that their differences are not insignificant and quite important. The statistics show that while the two approaches do not differ in the mean, the root mean square discrepancy between the two can reach over 50% of the scatter either of them exhibits. The repercussions of this we will discuss further below.

DISCUSSION

The geocenter series that were made available through the IERS campaign covered nearly every space technique that is capable of defining the geocenter. Due to various reasons, nearly every one of these series has a different resolution and that makes it difficult for point by point comparisons. Nevertheless though their statistical summaries indicate that most of them agree quite well. In particular, we examine the similarities of our series with those submitted by the Uni. of Texas/CSR group, which are also based on the SLR data from LAGEOS 1 and 2, but reported as 12-day averages. Figure 2 shows a 1-year portion of the two series covering the period 1995-96. At this large scale one can see that despite the different averaging interval, the two series are exhibiting similar trends during the same periods of time.

The level of difference between the two could be used as another measure of how reliably we can determine geocenter variations with the SLR technique today. In order to be able to compare the two series in a more rigorous way, we formed the 60-day running average for each one, as a four point average of the GSFC results and a five point average of the CSR results (60 days being the least common factor of 15 and 12 days). Figure 3 displays for each of the three components the smoothed series. The coherence between them is quite remarkable, even for the z-component which overall does show the largest discrepancy. Summary statistics for the smooth series (Table 4) indicate that indeed, the equatorial components agree extremely well, while in the z-component there is an 80% increase in the observed variation of the GSFC vs. the CSR series. Further inspection of Figure 3 suggests that this increase is caused primarily by a couple of isolated points in the middle of 1994 and 1995, and the estimates spanning the summer of 1996. This implies that the problem is probably due to the different weighting/treatment of some sites which are not participating throughout the period. We should also point out that depending on which approach we use to estimate the motion of the geocenter, we can easily see differences at the level of a few millimeters. This is something to keep in mind when contributions from different techniques/approaches are compared. A more careful and close inspection of the individual periods with above average discrepancies will be required to resolve this issue completely. At this point the differences, as seen visually from the figures displaying the original series as well as from the figures and statistics summarizing the two smoothed series, indicate that the reliability of these series is not better than 3-4 mm in each of the equatorial components and about 10 mm for the axial component.

We next examined the spectral content of the GSFC series to identify any significant concentration of variance at the most likely periods (biennial, annual, semi-annual and seasonal). The results are summarized in Table 5 and indicate that as far as the equatorial components are concerned, the majority of the variance is concentrated in the annual terms with an amplitude of about 1 mm. For the axial component however the spectrum is a lot richer throughout the band covered by the data. The biennial term shows an amplitude of 4 mm, the

annual ~ 3 mm, the semi-annual ~ 2 mm and the seasonal ~ 1.3 mm. Amplitudes at or below the 1 mm level would hardly be considered significant for this sample.

SUMMARY

We analyzed SLR data from LAGEOS 1 and 2 collected over the period 1993 up to the end of 1996 with the goal of defining a high resolution (15-day average) geocenter motion series. Our results indicate that the geocenter exhibits a markedly different behaviour in its motion on the equatorial plane vs. that along the axial direction. On the average the equatorial components vary by ± 10 mm peak-to-peak, while the axial component is more energetic and displays a ± 35 mm variation. The formal accuracy estimates of our results and comparisons with independent solutions indicate that the accuracy we can determine these motions at 15-day intervals is ~ 3 mm for the equatorial components and ~ 11 mm for the axial component. Our comparison of two different approaches in determining these motions indicates that at present we cannot reliably detect motions that are below the 2 mm and 8 mm level respectively.

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Table 1. Statistics for the results from the geometric approach.

Geometric Offsets	$-\Delta X$ [mm]	$-\Delta Y$ [mm]	$-\Delta Z$ [mm]
Minimum	-12.1	-10.1	-31.4
Maximum	9.9	9.2	33.4
Points	102	102	102
Mean	-1.6	-1.5	2.1
Std Deviation	3.7	3.9	12.6

Table 2. Statistics for the results from the dynamic approach.

Dynamic Offsets	$\sqrt{3a_e}C_{1,1}$ [mm]	$\sqrt{3a_e}S_{1,1}$ [mm]	$\sqrt{3a_e}C_{1,0}$ [mm]
Minimum	-7.7	-11.3	-25.8
Maximum	5.9	10.3	35.4
Points	102	102	102
Mean	-1.3	-1.2	3.5
Std Deviation	2.8	3.3	11.0

Table 3. Statistics for the difference between the results from the two approaches.

Residual Offsets	$\sqrt{3a_e}C_{1,1} - \Delta X$ [mm]	$\sqrt{3a_e}S_{1,1} - \Delta Y$ [mm]	$\sqrt{3a_e}C_{1,0} - \Delta Z$ [mm]
Minimum	-5.2	-5.4	-26.6
Maximum	6.2	6.1	28.4
Points	102	102	102
Mean	0.3	0.3	1.4
Std Deviation	2.0	1.9	7.8

Table 4. Smoothed SLR series summary statistics.

Series	Minimum	Maximum	Mean	RMS	Std Deviation
$\{\text{GSFC}-\Delta X\}_4$	-5.9	7.6	1.5	2.8	2.4
$\{\text{GSFC}-\Delta Y\}_4$	-7.8	11.3	1.2	3.1	2.9
$\{\text{GSFC}-\Delta Z\}_4$	-35.4	25.8	-3.4	10.4	9.9
$\{\text{CSR}-\Delta X\}_5$	-7.6	6.8	-0.3	2.8	2.8
$\{\text{CSR}-\Delta Y\}_5$	-8.8	14.0	0.3	3.5	3.5
$\{\text{CSR}-\Delta Z\}_5$	-20.5	14.0	0.0	5.5	5.5

Table 5. Spectral contents of the GSFC SLR analysis geocenter series.

Amplitude:	ΔX [mm]		ΔY [mm]		ΔZ [mm]	
Period [y]	cos	sin	cos	sin	cos	sin
2	-0.05	-0.24	-0.27	-0.19	-1.79	3.45
1	-0.30	-0.77	-0.61	1.02	1.67	2.24
1/2	-0.01	0.48	0.13	-0.01	-0.93	1.57
1/4	0.04	-0.56	-0.36	0.28	-0.66	1.14

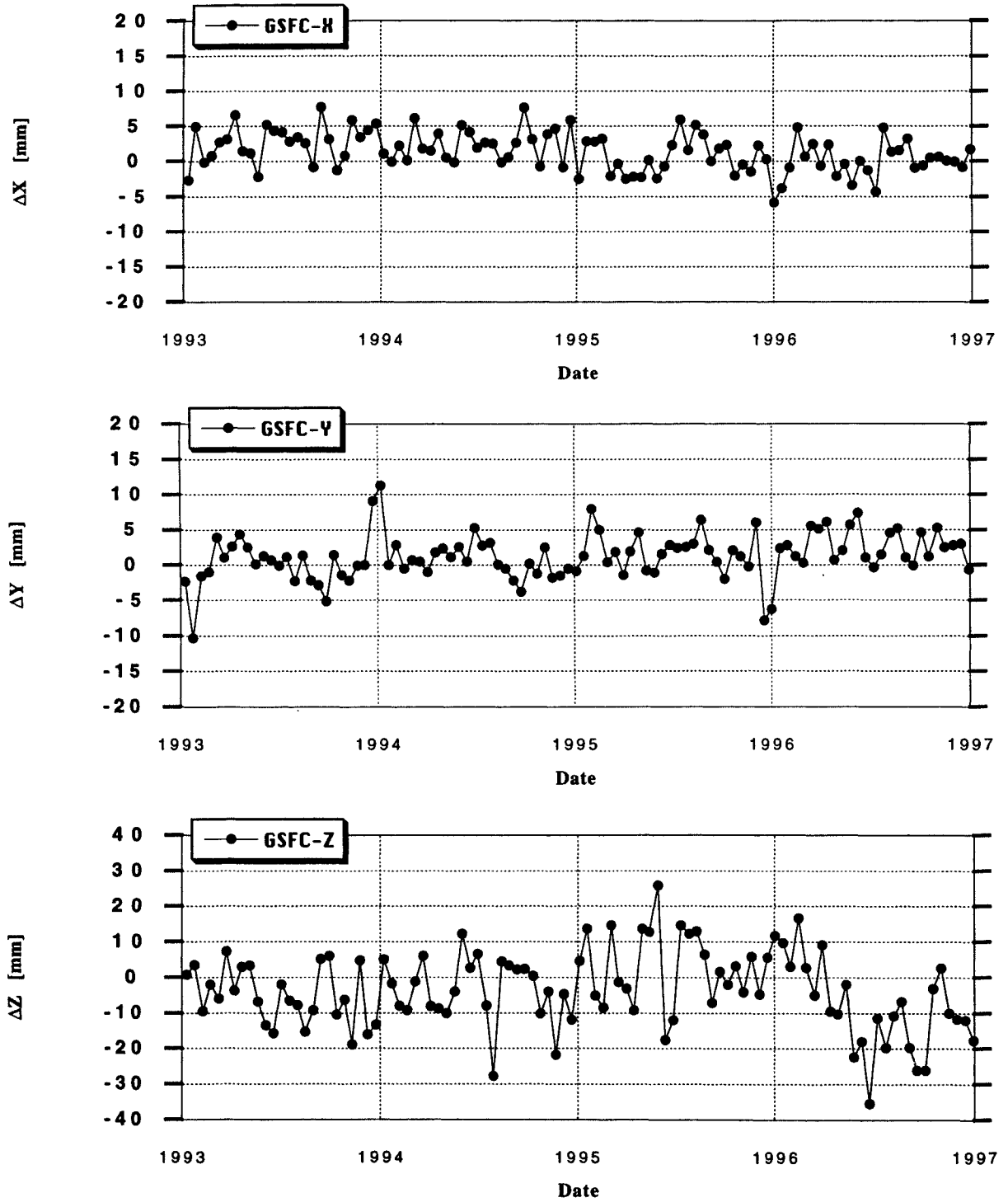


Figure 1. The GSFC SLR-based geocenter series with 15-day resolution for 1993-96.

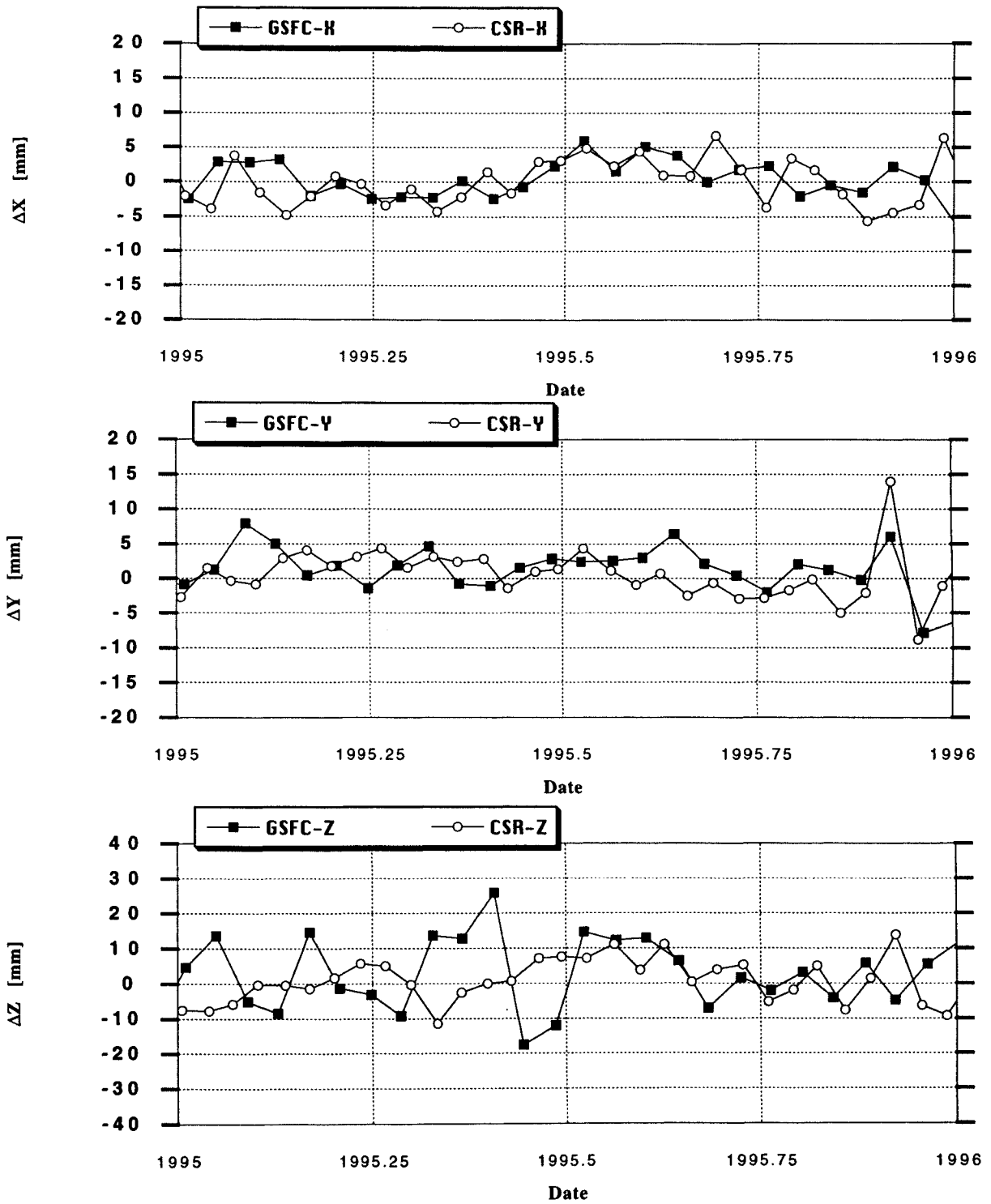


Figure 2. The motion of the geocenter in 1995 from two SLR analyses: GSFC and CSR series.

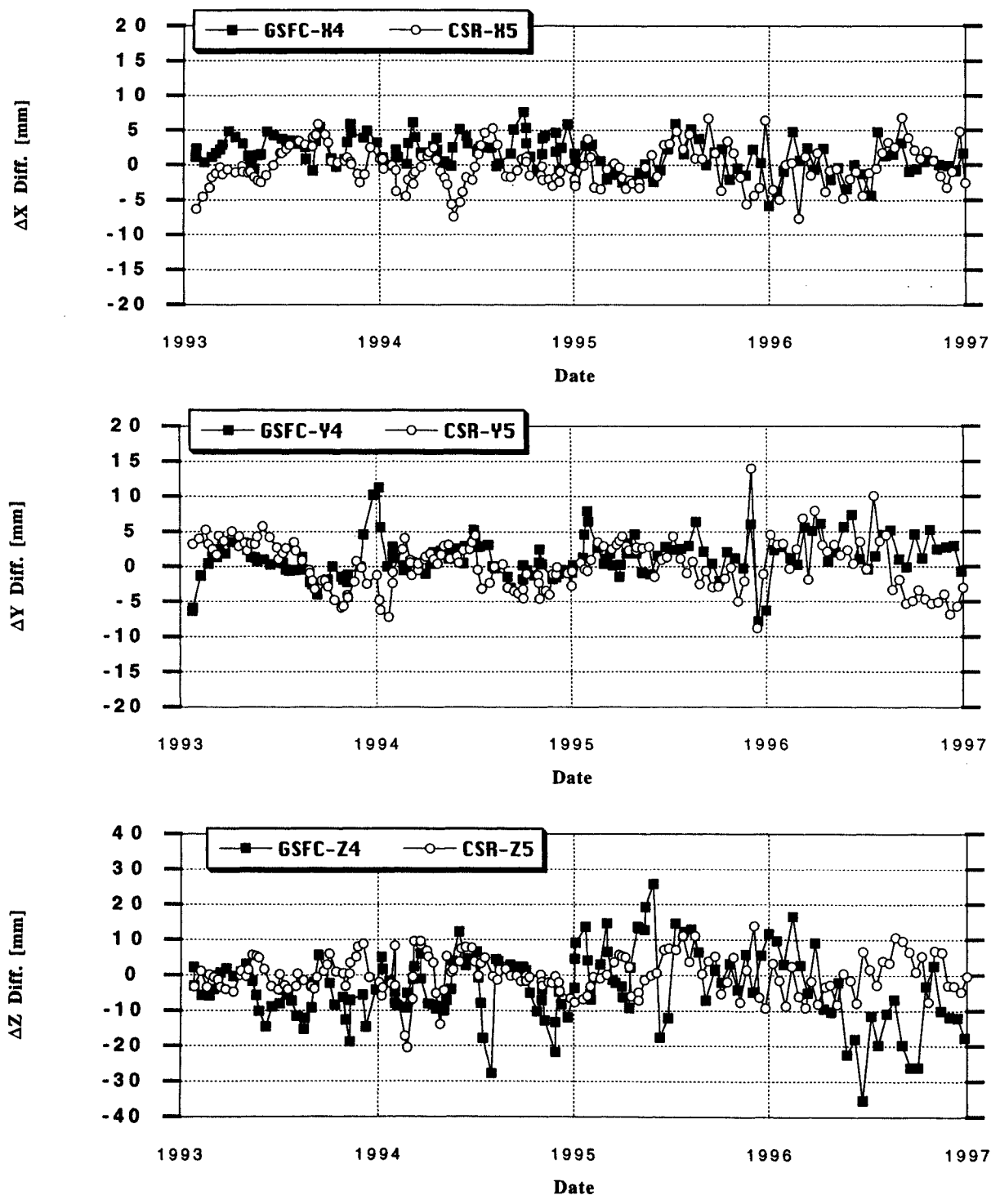


Figure 3. Smoothed series (60-day average), based on the original GSFC and CSR solutions.

OCEAN TIDE LOADING AND DIURNAL TIDAL MOTION OF THE SOLID EARTH CENTRE

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INTRODUCTION

Ocean tides imply mass movements on a global scale and whence the relative locations of the mass centre of the solid earth and that of the ocean are subject to temporal variations. Assuming that only the solid earth (and unless expressly noted otherwise: jointly the core) counterbalance the oceanic mass dislocation in order to maintain a uniformly moving centre of gravity of the entire planet, the offset of the solid earth mass centre from the joint mass centre due to ocean tides can be readily computed.

The conventional models for ocean loading displacements (McCarthy, 1996; Scherneck, 1991) do not include the motion of the frame origin; they specify only the displacements due to deformation and that these displacements are reckoned with respect to the centre of gravity of the solid earth. Note, however, that this concerns all spherical harmonic degrees including 1, which is an excentric mode.

The formulation of tidal motion in terms of a finite number of partial tides, each having a specific frequency, allows that at any location on the earth surface the loading tide displacement can be computed from a finite set of amplitude and phase parameters. The parameters vary significantly from place to place, reflecting an integrating property of the loading effect due to masses within some hundred kilometers radius around the observing point. The convention for the phase is to have zero phase of the astronomical tide gravity potential at the zero meridian. The same harmonic setup is suitable also for the centre of gravity movements of the solid earth.

The number of amplitude and phase parameters can be much lower than the number of tidal harmonics usually included in harmonic developments of the tide potential. The complex coefficient combining phase and amplitude of the effect can be interpolated as a function of frequency within each tide band, using a low order polynomial. A special interpolation method using sinusoids instead of polynomials is found in the orthotide formulation (Groves and Reynolds, 1975). The orthotide approach has been employed by the CSR group (Eanes and Bettadpur, 1995). In the interpolation the tidal spectrum must be stripped of waves pertaining to spherical harmonic degrees greater than two since the ocean response to these forcings is fundamentally different. At present, ocean tides excited by degree three tides and above are not included in the loading model. On the planetary scale we expect them to be 1/60 smaller than the degree two tides, and thus we dismiss them from the geocentre case.

The stations operating for the maintenance of geodetic reference systems are attached to the solid earth. According to our reasoning about the mass centre of the solid earth we submit that after reduction of the deformation component of loading tides the global network is seen to undergo small oscillations around the physical mass centre. It is this motion that will be termed—a bit misleadingly perhaps—geocentre tide.

The geocentre tide has the simple nature of a rigid translation. As a consequence, observing techniques that are based on simultaneous differences of positions or ranges like VLBI are inherently invariant to it.

To predict the tidal motion with respect to the joint mass centre it is practical to combine the two contributions. Interpolation of admittance can be applied before or after combination. The deformation can be added to the local solid earth tide as the latter is inherently free from global translation.

1 Until now ocean loading tide model did not include geocentre tide

The IERS recommended ocean loading tide model did not include the geocentre tide for the following reasons:

Whereas the deformation part obtained from different ocean tide maps is within relatively small bounds, the geocentre terms show considerable spread. Table 1 shows representatively the geocentre tide coefficients for the M_2 and O_1 tides. Hydrodynamic models of the ocean are relatively inaccurate as regards long-wavelength features since the dynamic terms are related to the gradient of the surface elevation. In this sense degree one efficient terms in the ocean are at the extreme low-admittance end of the signal that is passed through the gradient operator. In lieu of observational verification of degree-one oceanic tides or conversely the geocentre tides their inclusion in a reference standard would be premature.

As a second reason, the reference point for satellite orbits must be chosen consistently with the local site motion of the tracking stations. If the geocentre tide were applied at observing stations without the orbit referring to the joint mass centre, a geocentre tide with the negative sign would be introduced into the reduced observations. Thus, there is a risk of inconsistent application of the geocentre tide.

In the near future, however, a higher level of consistency can be reached. The CSR3.0 ocean tide model appears to be suitable for a number of effects (geopotential, geocentre, ocean loading). The long-period tides can in this context be treated as a static equilibrium response, which is the assumption of CSR3.0. The fortnightly ocean tide might show significant departures from a static response; due to ongoing efforts of the Le Provost group (Lyard, 1998, pers. comm.) a dynamic M_f model is available since May 1998.

2 Estimating ocean loading tides from GPS

Single point positioning results can be obtained from GPS with GIPSY software (Webb and Zumberge, 1993; Zumberge et al., 1997). We have chosen this processing mode since it does not perform range differencing, and since it is free from the interdependencies of motions and errors at simultaneous observations typically experienced in network solutions. Thus the data is expected to preserve a more complete set of range variations between the satellite and the receiver. Spacecraft positions are taken from JPL orbit solutions which include an accurate clock parameter as a prerequisite to solve single point positions accurately. The huge amount of available observations allows to solve for long, almost uninterrupted time-series at sampling rates suitable for tide analysis.

Positions were estimated with the GIPSY Kalman filter at two hours interval, atmospheric parameter at

Table 1: Coefficients for geocentre tides, cos and sin factors, respectively for motion along the three cartesian components Z, X and Y. Unit is millimetre. The data are based on ocean tides due to L - Le Provost et al. (1994), C - CSR3.0 (Eanes and Bettadpur, 1995), S - Schwiderski and Szeto (1981). Model CW lists the geocentre results of Watkins and Eanes (1997).

Tide	Model	Z		X		Y	
		cos	sin	cos	sin	cos	sin
M2	S	-0.60	-0.84	-4.29	-0.68	2.98	-1.71
M2	L	-1.68	-2.23	-0.49	-0.67	0.04	-0.77
M2	C	-1.44	-1.53	-1.46	1.30	1.34	0.05
M2	CW	-2.72	-1.50	-2.38	0.34	1.67	0.62
O1	S	-0.52	2.47	-1.00	-0.03	-1.02	-1.09
O1	L	-1.04	3.87	-0.88	-0.61	-0.93	-0.99
O1	C	-0.40	2.93	-1.11	-0.19	-0.97	-0.85
O1	CW	-0.46	3.27	-2.85	-0.64	-1.65	0.45

5 minutes interval assuming a random walk noise model of the zenith delay. Each sample was taken to represent the mean position of the station at the central time of the two-hour interval. The 3-D series were transformed into a local system with east, north, and vertical axes. Solid earth tide displacements were subtracted as usual in GIPSY.

Each component of the position time series was analyzed for remaining tides by least-squares estimates of complex admittance parameters for tidal wavegroups which are constructed from the tide potential of Tamura (1987). Admittance parameters for a linear trend and for a time series of predicted atmospheric loading displacements were also included in the analysis.

Computation of atmospheric loading followed closely the method for ocean loading tides, the major difference being that loading occurs on land, and that the inverse barometer assumption suggested us to exclude waters with a depth greater than 300 m from being loaded. As a side-effect of the data preparation, geocentre tides computed from atmospheric pressure were made available to the community (cf Appendix). They are based on ECMWF ground-level fields at six hours interval.

The results are compared to ocean loading parameters computed along the lines of Scherneck (1991) and IERS Conventions (McCarthy, 1996) with the following modifications:

- Loading deformations (i.e. excluding geocentre tide) due to ocean tide models of Schwiderski and Szeto (1981) (shorthand: S), Le Provost et al. (1994) (L), and CSR3.0 (Eanes and Bettadpur, 1995) (C);
- Adding the geocentre tide as derived from each of these models to the deformation (SG, LG, CG).
- Adding a degree one co-oscillating ocean tide to the wet nodes of CSR3.0 in order to obtain a geocentre tide compatible with recent SLR observations (Watkins and Eanes, 1997) and computing loading deformation and geocentre tide (CWG).

The CSR3.0 model was always masked with the land-sea distribution of the L model as it specifies many wet nodes at obvious land locations.

2 Discussion

The least-squares analysis results show clearly that ocean loading tides can be resolved in GPS data at the 1 mm level. Observed lunar species correlate well with the models in all three spatial components. Few authors have looked at the horizontal components before. In the light of the small error ellipses the data appears powerful and promising. Exploring the relation between the formally derived sigma and the post-fit residual χ^2 , the sigma shown on the horizontal components is a cautious estimate by a factor of typically 1.5. For more explicit results we refer to the sideshow, see Appendix.

We show three typical cases in the form of phasor graphics, Reykjavik, Iceland (M_2) - figure 1; Irkutsk, Siberia (M_2) - figure 2; and Mauna Kea, Hawaii (O_1) - figure 3. Solar tide observations are not further interpreted since re-initialisation of the Kalman filter occurred at a 24 hour interval. We also hesitate to interpret sidereal tides as large effects at K_1 and its upper harmonics are found. They might be related to orbit errors, features that change only slowly in time when watched in a nonrotating frame). Thus, the leading partial tides that can be studied with prospective confidence are lunar species, M_2 , N_2 , O_1 , and Q_1 . The long duration of the time series warrants the required spectral resolution of the major sidereal, solar, and in particular the lunar waves.

The general picture emerging from the GPS analysis is that

1. any of the submodels explains the observed motion equally well; reduction of the observed signal RMS is regularly better than 50 percent.

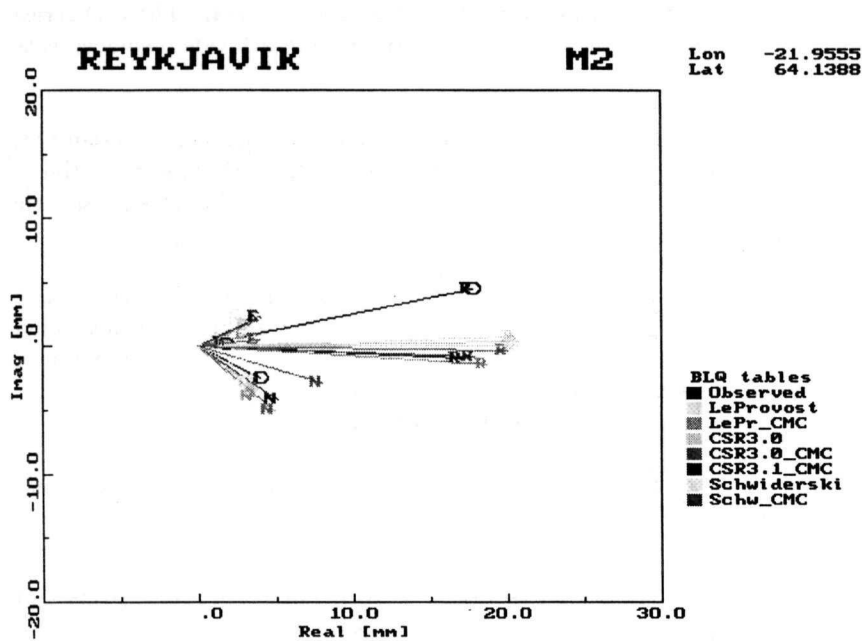


Figure 1: Phasor plot of tide analysis results. Solid earth tide has been reduced from the observations. The observations are shown in black with an error ellipse according to the a priori variance. Ocean loading tide models have been grey-coded with dark greys for models that include the geocentre tide and light greys for those that do not. From the post-fit error we find that the ellipse can be scaled up by 1.5 in the case of vertical displacement and down by 0.75 in the case of the horizontal components to achieve $\chi^2_\nu = \nu$.

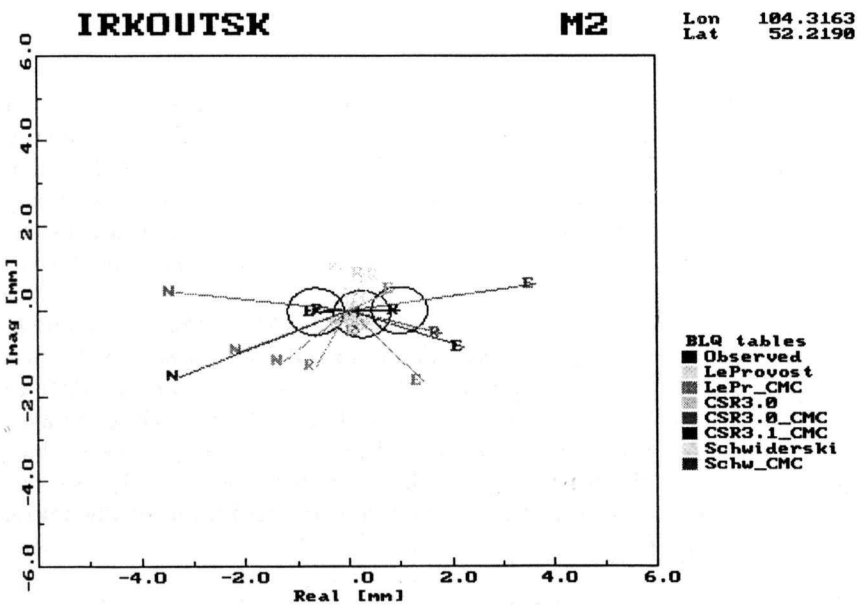


Figure 2: Far inland station Irkutsk exhibits relatively strong geocenter motion as this global translation affects all locations equally much while ocean loading is rather small. Other caption information of 1.

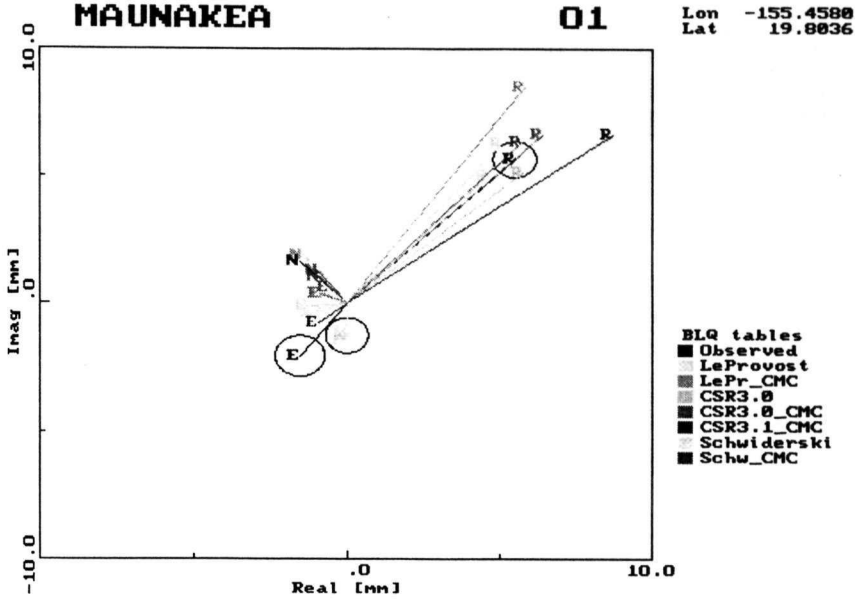


Figure 3: Diurnal residual tide O_1 at Mauna Kea, Hawaii. More caption information cf 1.

- there are large residuals in terms of the formal confidence limits. Whether these residuals are due to systematic errors in the data analysis process or due to mismodelling remains to be determined.
- most importantly, however, residuals increase when geocentre tides are included. This is most probably relating to the fact that geocentre tides were ignored in the process of computing the orbits. The computed orbits appear to be rather invariant to—at least short- period—rigid translations.

A superficial measure of the over-all impact of the loading options is the sum of squares of the tidal residuals at each station. The zero option, no ocean loading motion, is included. The sum

$$S_k^2 = \sum_{n=1}^N \sum_{c=1}^3 |u_{nc} - \hat{u}_{knc}|^2$$

$$k = \text{nil, S, SG, L, LG, C, CG, CWG} \quad (1)$$

stretches over the three spatical components and $N = 4$ lunar species as detailed above. The sums are presented in Table 2.

CONCLUSIONS

It is highly a matter of decisions to be taken at the satellite orbit computation centres whether or not to correct ranges observed at tracking stations for geocentre tides. For those developers who plan to employ the ocean loading model during the coming years there may be a desire for parallel options. End users need to carry out their procedures consistent with the orbit products etc. they acquire. In order to serve these demands and to accomplish a higher degree of consistency, the following suggestions will be made as regards the recommended IERS procedures:

- Ocean loading models will come in two versions, with and without the geocentre terms. See Appendix.
- The deformation as well as the geocentre tide will be computed with the CSR3.0 ocean tide as the basis.

Table 2: Root sum squares of lunar tides as observed with GPS, reduced by the ocean loading models based on ocean tides due to L - Le Provost et al. (1994), C - CSR3.0 (Eanes and Bettadpur, 1995), S - Schwiderski and Szeto (1981); modifier G designates inclusion of geocentre tide, CWG is CG modified to yield the geocentre motion of Watkins and Eanes (1997). Values are millimetres, σ designates error in determination of a single tide wavegroup.

Site	σ	nil	L	LG	C	CG	CWG	S	SG
Reykjavik	0.5	19.6	5.5	7.8	6.0	7.6	11.5	6.1	7.9
Sundsvall	0.5	3.7	2.8	5.3	2.8	4.9	9.5	3.2	6.4
Pie Town	0.5	5.6	1.9	5.3	2.0	4.9	9.0	2.4	6.1
HartRAO	0.8	16.4	12.5	13.2	11.8	10.8	12.7	12.6	13.4
Irkoutsk	0.5	2.1	2.7	5.8	2.8	5.4	10.0	2.7	6.9
Ascension	0.6	13.0	13.5	14.1	12.9	12.4	15.0	11.7	9.2
Yaragadee	0.5	7.5	14.6	16.3	13.8	15.0	16.8	13.9	15.2
Mauna Kea	1.1	14.5	3.6	7.2	6.1	8.7	12.3	4.0	7.4
Mendeleevo	0.5	2.6	1.7	5.5	2.0	5.0	9.4	2.0	6.5
Onsala	0.9	14.1	12.6	14.1	12.6	12.9	16.1	12.4	15.0

3. The recommended model in connection with GPS and VLBI will be the geocentre-free model OL-C, unless orbit computation centres make the transition to orbits centred on a tide-free origin.
4. The recommended model in connection with satellite methods that use a tide-free frame origin will be OL-CG.
5. The other models will be earmarked as being for experimental purposes.

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APPENDIX

File names

Air pressure driven geocentre motion: [ftp://gere.oso.chalmers.se/pub/hgs/geoc/airp.\\$MOD.cmc](ftp://gere.oso.chalmers.se/pub/hgs/geoc/airp.$MOD.cmc) where **\$MOD** is **ib** (inverted barometer), **noib** (no inverted barometer) or **ocib** (inverted barometer with inforced ocean mass conservation). Explanations in <ftp://gere.oso.chalmers.se/pub/hgs/-INDEX.html>.

Geocentre tide coefficients equivalent to table 1: [ftp://gere.oso.chalmers.se/pub/hgs/geoc/\\$N.cmc](ftp://gere.oso.chalmers.se/pub/hgs/geoc/$N.cmc) where **\$N** is **S**, **L**, **C** or **CW** is in the text above.

A sideshow with tide analysis results and colour images of the kind of figures in this report can be visited at <ftp://gere.oso.chalmers.se/pub/hgs/4fhw/>.

GPS, DORIS and SLR combined geocenter motion from reference frame time series analysis

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ABSTRACT *The improvement in terms of precision of Space Geodesy measurements makes it possible to study global geophysical phenomenas. The Earth's center of mass variations became recently a subject of interest in Space Geodesy. Satellite Laser Ranging analysis centers have computed, for a few years, time series of geocenter positions which are coherent with theoretical models. The DORIS technique, more sensitive than GPS to Earth's gravity, is probably appropriate to compute such time series. The present paper, following a scientific campaign organised by the International Earth Rotation Service during 1997, is focused intercomparison of the dynamic techniques applying various signal analysis methods.*

1 INTRODUCTION

The Institut Géographique National team has been involved in the IERS activity for 10 years. The basic philosophy of all the works done in this field at IGN, as well as IERS central bureau, is to intercompare the data from Space Geodesy techniques, in order to detect, and eventually correct, the specific systematic errors that can be observed in this process. This way of thinking is the one chosen in this study and is a key element in the debate relative to the ability of Space Geodesy to monitor geocenter variations. In fact, the aim of this paper is clearly to crosscheck some Space Geodesy test data in order to make it possible to get an objective view of the coherence of Space Geodesy technique in the Geocenter motion determination. Furthermore, a complementary goal of this study is to attempt to combine the information when it is possible. Nevertheless, combining signals resulting of different adjustment is a bet. That's why, if one wants to combine various data in the view of geocenter determination, it is necessary to come back to the reference frame support, namely the set of coordinates, and to combine this type of data. It should be emphasized that this is possible only because there is an identification between the origin of the reference frame and the center of gravity of the Earth. This is generally true, but in a stochastic context, it can be argued that this is only an approximation.

2 MEASUREMENT METHODOLOGY

Generally speaking, the Geocenter is identified as the center of masses of the Earth. Its instantaneous position should be accessible to artificial Earth satellites. This assumption leads to the study of the variations of the origin of the frame in which is expressed the orbit of the satellite. When the station coordinates are adjusted in the same estimation process as the satellite orbit, the reference frame of the orbit parametrization should be the same as the underlying reference frame of the set of coordinates. The two approaches to determine reference frame origin variations and described hereafter are based upon time series of station set of coordinates.

Let us suppose that the geocenter is free of motion during the time span of an orbit arc. The gravitation force is radially directed to this “instantaneous” geocenter. If, in addition, we suppose that the gravity field, in steady state, doesn’t depend on the geocenter position, the reference system in which the orbit is computed is centred on the instantaneous geocenter. Thus, sets of coordinates carry the instantaneous geocenter information. Let us suppose now, that the orbit of a satellite is analysed through successive orbit arcs. Then each orbit arc can be considered as the realization of the instantaneous reference system. It is then possible to identify the geocenter variations in the way that the tracking stations move together. This leads to directly compute the geocenter motion from the orbit computation.

2.1 Comparisons of individual sets to an external reference

This approach consists of comparing each successive sets of coordinates independently to an external reference. In detail, Helmert transformation parameters are adjusted between individual sets and the reference, and the translation parameters are identified to the instantaneous geocenter position, averaged over the span of the individual set. The adjustment model is presented in Eq. 1. The first equation is the observation equation concerning the i^{th} station at time t_s (i.e. s^{th} set ; difference between the individual set (X_i^s) and the reference coordinates (X_i^0)), whereas the transformation parameters θ^s are estimated through a least-square adjustment and by the use of a design matrix A computed with approximate coordinate values¹.

$$\begin{cases} X_i^s(t_s) - X_i^0(t_s) \cong A_i \cdot \theta^s(t_s) & (\Sigma_i^s + \Sigma_0) \\ A_i = \begin{pmatrix} 1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 \\ 0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 \\ 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 \end{pmatrix} \\ \theta^s = (T_x^s \ T_y^s \ T_z^s \ k^s \ \varepsilon^s \ \psi^s \ \omega^s)^T \end{cases} \quad (1)$$

The problem of this method is that the estimated transformation parameters ($T_{x,y,z}$ in Eq. 1) are disturbed by the external reference error. The appropriate method is to take into account the variance over the external solution in the estimation process. Nevertheless, the external reference cannot insure the homogeneity of translation parameters in time, especially when the quality and the global distribution of the network used to generate individual sets change with time.

2.2 Comparison of individual sets to an internal reference

In order to avoid the previous problem relative to the disturbance due to the external reference, an internal reference deduced from the whole time series can be used. Basically, it is possible to compute in the same estimation process (Eq. 2) both an internal reference and a set of transformation parameters between individual sets and the combined one.

$$X_i^s(t) \cong (I \mid (t_s - t_0)I \mid A_i) \cdot \begin{pmatrix} X_i \\ \dot{X}_i(t_0) \\ \theta^s(t_s) \end{pmatrix} \quad (\Sigma_i) \quad (2)$$

The method is exactly the method used for ITRF-type combinations. Extending this principle, it is therefore possible to combine informations from various sources, while these sources have the same time sampling by the use of a constraint between transformation parameters. This method has also the advantage to smooth the data, while a temporal connection between sets of data is introduced by the use of the model (positions + velocities), as it is not the case with the different comparisons computed at different times of section 2.1.

3 SIGNAL ANALYSIS

3.1 Regression analysis

For each time series that have been obtained through the method explained above, a regression has been carried out in order to determine the amplitude and phase of a semi-annual and an annual term of excitation. A constant term as well as a trend has also been derived in order to express all the time series with respect to the same reference system. For a signal $s(t)$, the analysis is carried

¹The sign $\cong$ means equality between random variables

out through the following way (annual term indexed $_1$ and semi-annual term indexed $_{1/2}$; the phase is computed with respect to the first of January) :

$$s(t) \cong A_0 + A'_0t + A_1\cos(\omega_1t + \phi_1) + A_{1/2}\cos(\omega_{1/2}t + \phi_{1/2}) \tag{3}$$

3.2 Wavelet analysis

In order to investigate the whole spectrum of previous signals, a wavelet analysis has been carried out. The interest of wavelets with respect to Fourier analysis is that it does not postulate the time invariability of a particular frequency during the whole data span. The idea is to associate an instantaneous frequency to the signal and let the possibility to analyse the signal as a frequency changing signal.

• A signal $[t \in I \subset \mathbb{R} \longmapsto s(t)]$ • Wavelet transform $\mathcal{T}_s(t,a)$:	
$\begin{cases} \mathcal{T}_s(t,a) &= \int_{\mathbb{R}} s(x)\overline{\Psi}_{(t,a)}(x)dx \\ \Psi_{(t,a)}(x) &= \frac{1}{a}\Psi\left(\frac{x-t}{a}\right) \\ \Psi(x) &= e^{i\omega_0x}e^{-x^2/2} \end{cases} \quad \text{(Morlet Wavelet)}$	
• graph of $\mathcal{T}_s(t,a)$ with	$\begin{array}{ll} t &: \text{X-axis} \quad \quad \quad (\text{time}) \\ a &: \text{Y-axis} \quad (\text{scale} \leftrightarrow \text{period}) \end{array}$

Table 1: Wavelet transform formulae

Wavelet transform can be seen as a generalization of Fourier transform : it is a basic decomposition into the frequency space, but this space has an other dimension which is time (see Tab. 1).

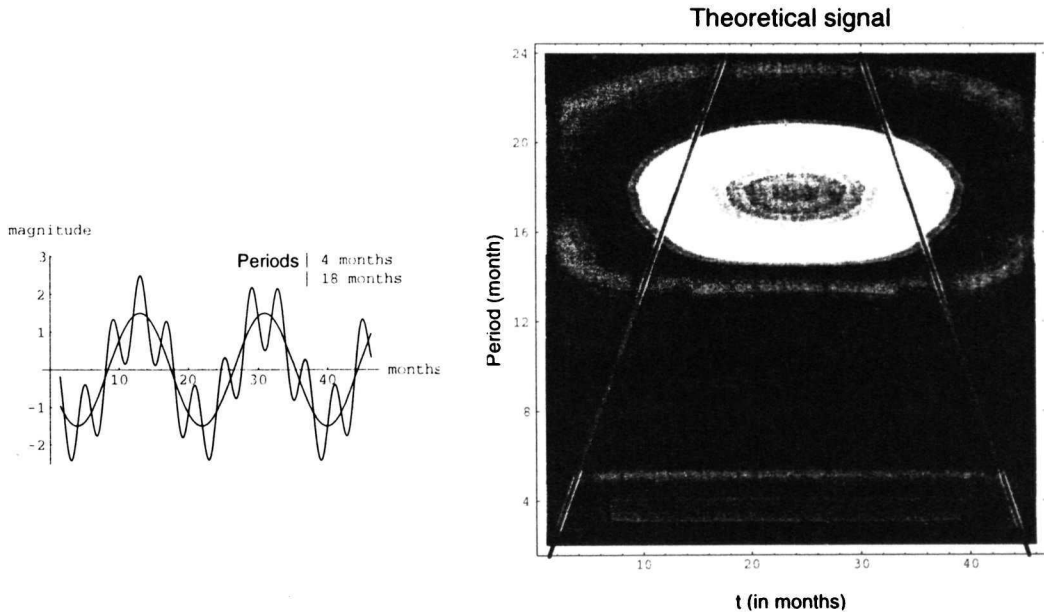


Figure 1: Wavelet analysis of a signal without frequency change

Fig. 1 shows the graph of the wavelet transform of a pure invariant frequency signal, and Fig. 2 shows the impact, on the wavelet transform, of a change in the frequency, during the whole span, in the modulation signal. The gap is perfectly identified by the wavelet transform, while, of course, Fourier analysis couldn't identify it as it pre-supposes the invariability of the signal's frequency during the whole span. An other property of wavelets, showed in Fig. 1 and that has to be kept in mind, is the limitation that the bounded interval of the signal induces on the detection of a specific period : an information window is defined, in which an existing signal can be detected ; outside this window (red lines), there is not enough data to find anything.

Finally, one can say that wavelet transform is a technique that is closer to the physical behaviour of stochastic processes and then, is a major tool for analysing such signals.

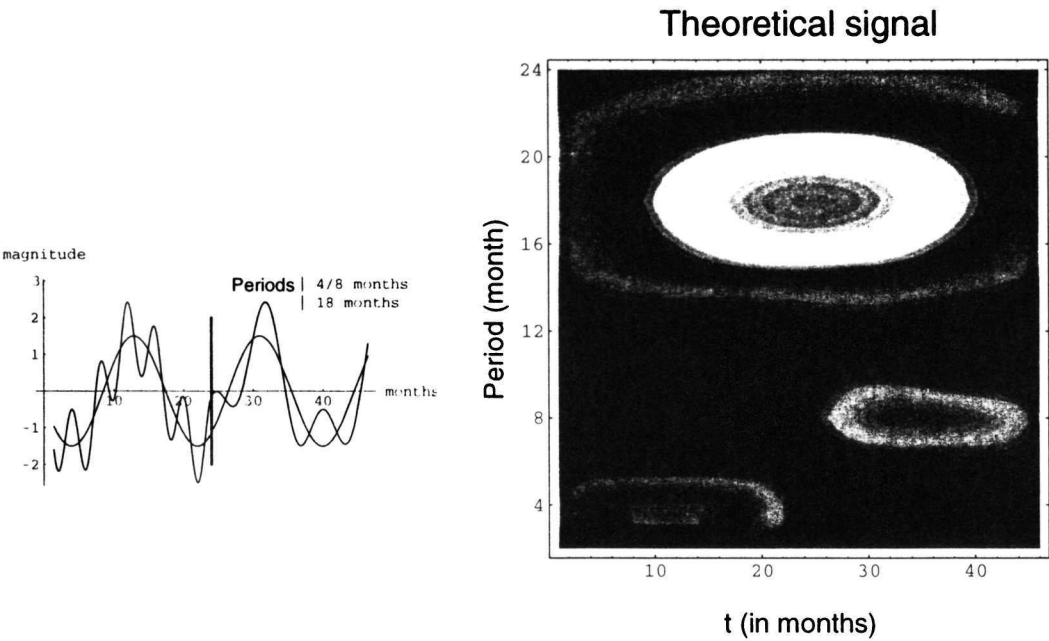


Figure 2: Wavelet analysis of a signal with frequency change

4 THE SETS OF DATA AND REGRESSION ANALYSIS

This section is dedicated to the analysis of the time series that have been used for this study. Some come directly from the web site of GEOC, and some others are deduced from sets of coordinates combination made at IGN. For all the time series of geocenter positions, a linear regression has been performed in agreement with Eq. 3. The results of this regression have been analyzed in amplitude and phase.

Time series	A_1 <i>mm</i>	φ_1 <i>deg.</i>	$A_{1/2}$ <i>mm</i>	$\varphi_{1/2}$ <i>deg.</i>
LASER-CSR	2.1 ±0.64	-58.8 ±8.9	1.2 ±0.64	77.2 ±16.
DORIS-GRGS	3.2 ±1.0	-153 ±9	1.6 ±1.0	117 ±18
DORIS-IGN	5.6 ±5.	79.7 ±25.	4.2 ±4.8	-160. ±34.
GPS-JPL	5.3 ±4.8	-15.0 ±23.	7.3 ±4.1	-98.3 ±19.
Combined GPS-JPL + DORIS-IGN	2.4 ±3.2	-54. ±40.	2.9 ±3.	-81.3 ±33.

Table 2: Annual and semi-annual components in X

4.1 Satellite Laser Ranging

This technique is the one which has the greatest potential since it is sensitive to variations of geocenter positions : the dynamic of the satellite is well known and allows a very deep analyse of gravitational effects among which are geocenter variations. The results presented in Tab. 2, 3, 4 and Fig. 3 have been obtained by the Center of Space Research (CSR) and submitted during IERS geocenter campaign (Eanes et al., 1997). One can see that the uncertainties over regression parameters are the smallest that have been obtained, which confirm the sensitivity of this technique to gravity field. This also justify the interest of this technique in the field of geocenter motion. It can also be seen that the Laser Ranging geocenter variations have an amplitude which is compatible with theoretical prediction (Dong et al., 1997). SLR seems to be the only technique compatible with theory. To a smaller degree, DORIS seems to be able to confirm this magnitude (see §4.2).

Time series	A_1 mm	ϕ_1 deg.	$A_{1/2}$ mm	$\phi_{1/2}$ deg.
LASER-CSR	3.2 ± 0.73	59.5 ± 6.8	0.68 ± 0.74	111. $\pm 31.$
DORIS-GRGS	4.2 ± 1.3	60 ± 9	0.9 ± 1.3	-77 ± 42
DORIS-IGN	9.3 ± 2.2	-39.7 ± 6.7	1.9 ± 2.2	-123. $\pm 32.$
GPS-JPL	8.6 ± 2.5	174 ± 7.2	1.5 ± 2.2	120. $\pm 46.$
Combined GPS-JPL + DORIS-IGN	2.4 ± 3.2	-54. $\pm 40.$	2.9 $\pm 3.$	-81.3 $\pm 33.$

Table 3: Annual and semi-annual components in Y

Time series	A_1 mm	ϕ_1 deg.	$A_{1/2}$ mm	$\phi_{1/2}$ deg.
LASER-CSR	2.9 ± 1.6	-44.1 $\pm 16.$	0.37 ± 1.6	-64.2 $\pm 130.$
DORIS-GRGS	5.6 ± 5.2	51 ± 47	0.9 ± 5.2	-48 ± 159
DORIS-IGN	19. ± 5.1	168. ± 8.4	11. ± 5.4	-63.4 $\pm 14.$
GPS-JPL	19. ± 6.7	-32.0 ± 9.9	17. ± 7.3	-30.2 $\pm 11.$
Combined GPS-JPL + DORIS-IGN	12. $\pm 10.$	41.7 $\pm 26.$	14. ± 9.7	-62.7 $\pm 22.$

Table 4: Annual and semi-annual components in Z

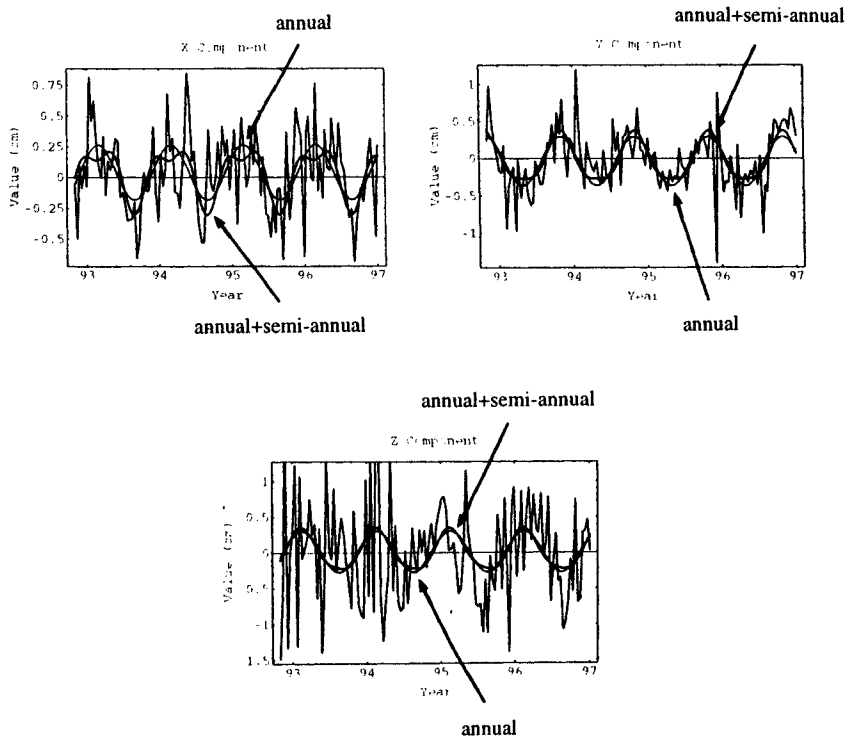


Figure 3: LASER geocenter components

4.2 DORIS

Two analysis centers provided data during IERS geocenter campaign : the Groupe de Recherche en Géodésie Spatiale (GRGS - Toulouse) and the Institut Géographique National (IGN). The results of the linear regression can be found in Tab. 2, 3 and 4. The DORIS-GRGS time series comes from a set of transformation parameters identified to geocenter position (according to section 2.1) (Bouillé and Cazenave, 1997). The DORIS-IGN time series comes from a section 2.2-type combination where transformation parameters between all the individual sets and the combined one have been estimated in the same run (Sillard et al., 1997; Willis et al., 1997).

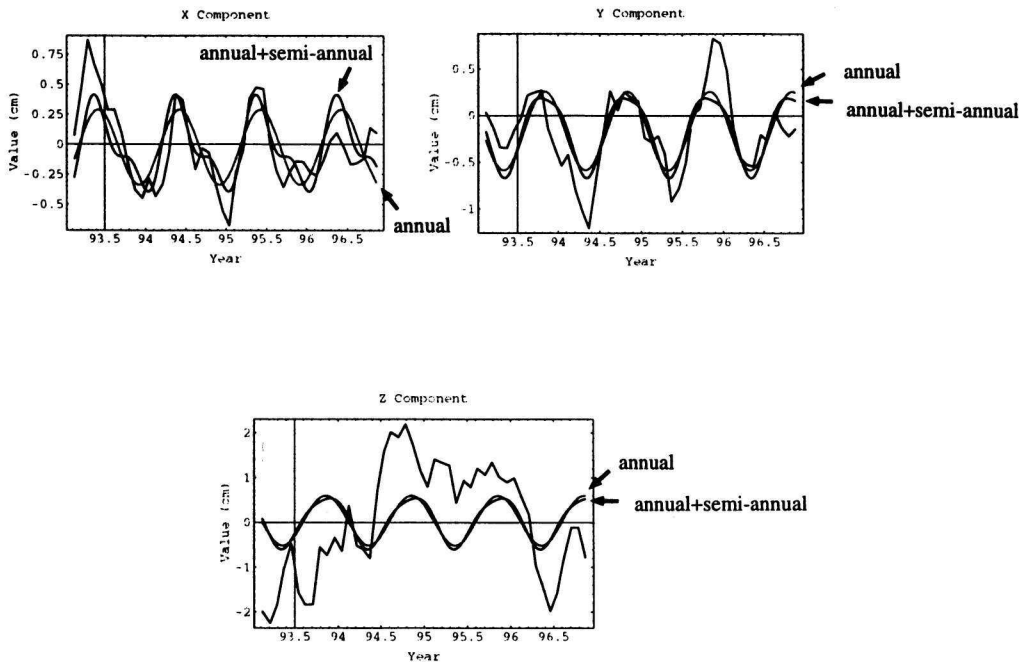


Figure 4: DORIS-GRGS geocenter components

The conclusion that can be drawn from the results is that the determinations are not really coherent : the amplitudes of IGN signals are systematically overestimated with respect to GRGS results. The phases are not more coherent. One of the main conclusion, apart from the previous one, could be that, in no case, the semi-annual signal seems to be significant. Finally, it is necessary to be careful on these results which should suggest that DORIS is not really capable to determine geocenter variations at the moment.

4.3 GPS

The GPS technique has a disadvantage with respect to previous techniques : the altitude of GPS satellites is much higher than DORIS or SLR, which leads to the fact that GPS is less sensitive than other techniques to the details of the gravity field. Nevertheless, it is interesting to study the use that can be done of GPS measurements to improve other techniques.

The GPS geocenter time series has been obtained through a combination (see §2.2) of weekly time series of sets of station coordinates computed by Jet Propulsion Laboratory (JPL) and provided to International GPS Service (IGS) (Hefflin, 1997; Sillard et al., 1997).

One can see that the results are slightly different from other results, neither more nor less coherent. Fig. 6 shows the original curve together with adjusted annual and semi-annual curves.

4.4 Combined DORIS and GPS determination

Finally, and it is an advantage of the method described in section 2.2, a simultaneous combination from GPS-JPL and DORIS-IGN sets of station coordinates has been carried out. The transformation

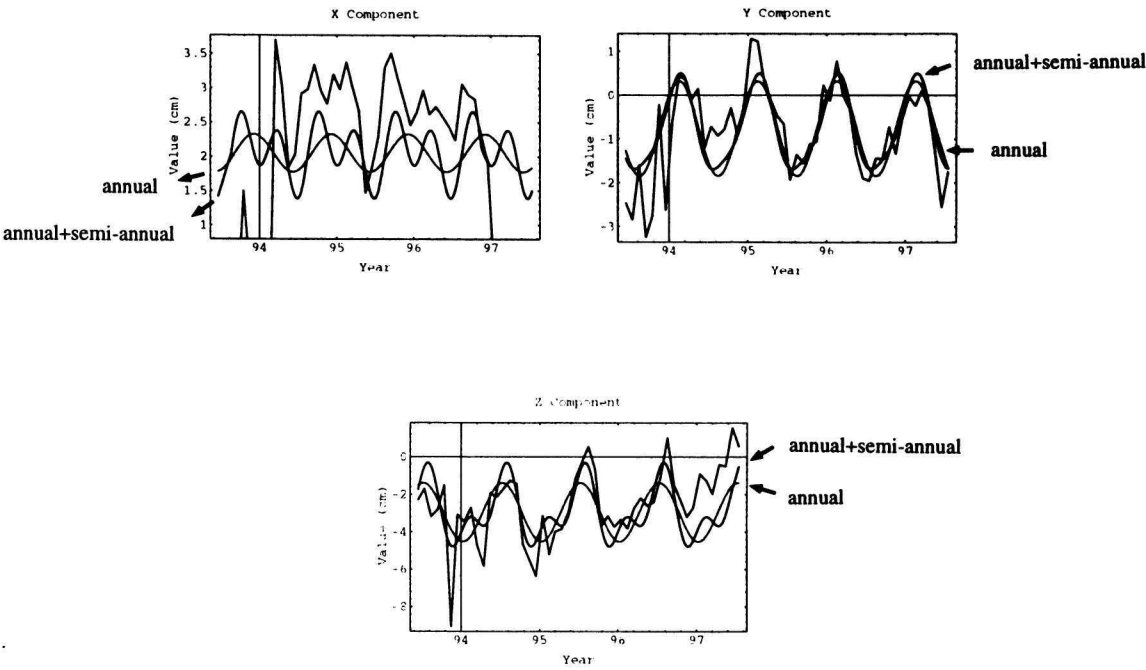


Figure 5: DORIS-IGN geocenter components (red : annual ; blue : annual + semi-annual)

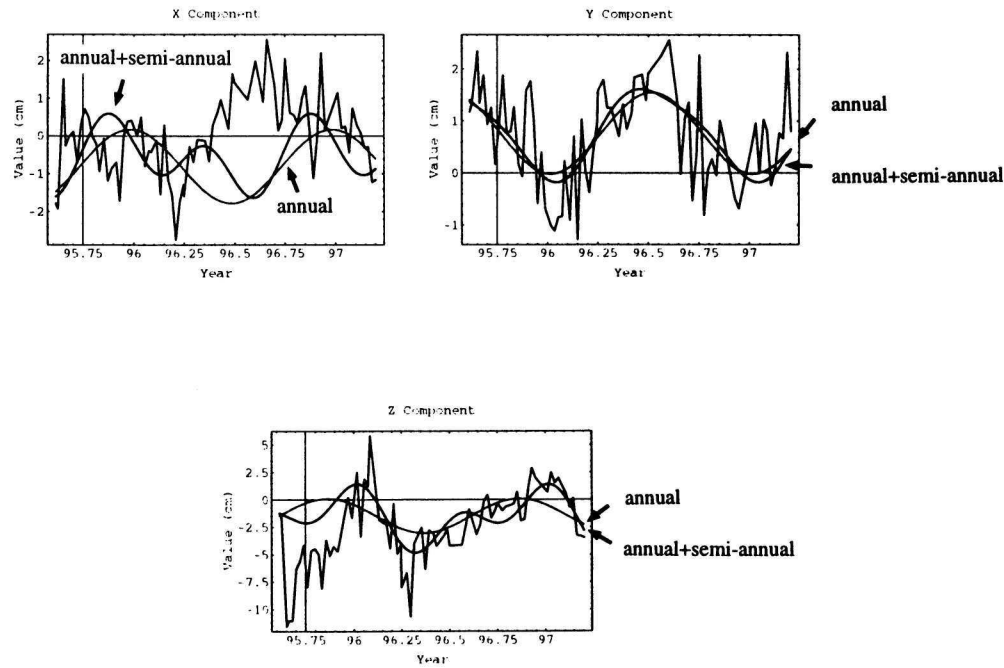


Figure 6: GPS-JPL geocenter components

parameters between the combined solution on one hand, and the individual DORIS and GPS sets on the other hand, were constrained to be equal at the same dates. The combination is based upon local eccentricities used for ITRF96 computation between DORIS and GPS collocated stations. Fig. 7 shows the plots of the resulting geocenter component time series (Sillard et al., 1997).

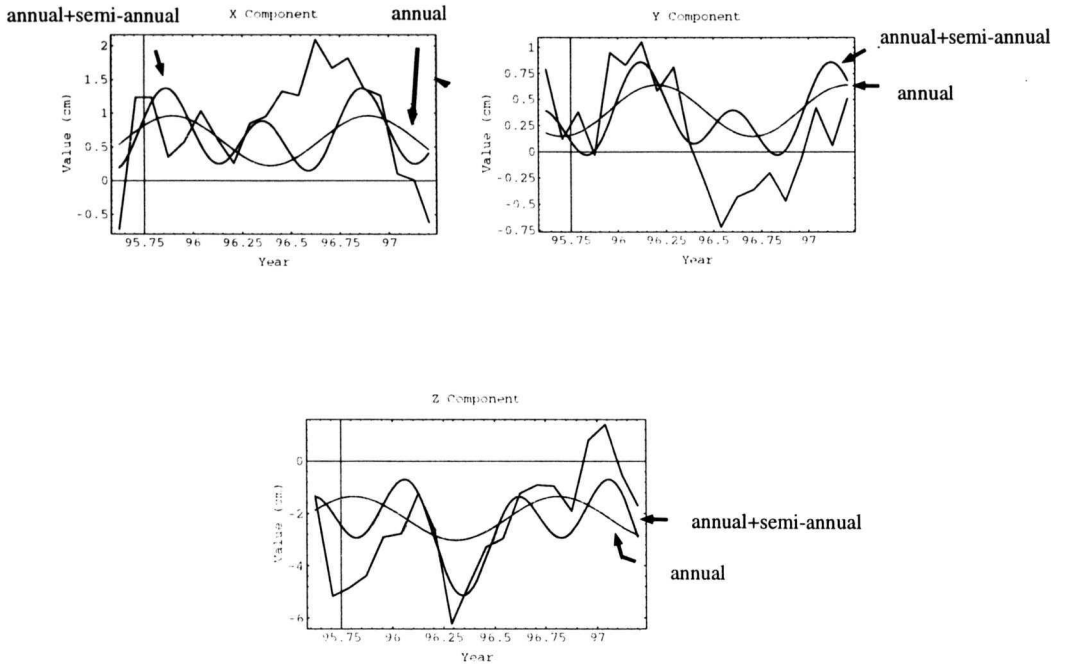


Figure 7: Combined DORIS-IGN and JPL-GPS geocenter components

As expected, since the DORIS and GPS time series are not really coherent, the combined signal has a smaller amplitude than original ones (DORIS and GPS). The combined signal is closer to the theoretically expected level and therefore more satisfying than individual solutions, even if the resulting signal is poorly significant. This technique could be used routinely in the view of geocenter motion monitoring, especially if SLR technique was able to produce time series of set of station coordinates.

5 COMPARISON OF THE REGRESSION RESULTS AND WAVELET ANALYSIS

In order to summarize the regression estimates, it is interesting to study the results in the phase space. It will then be easy to estimate the level of consistency between adjusted signals. Fig. 8 shows the graphics for annual analysis, and Fig. 9 shows the graphics for semi-annual analysis. The scale of the graphics is the millimetre, and the phase is measured with respect to X-axis.

A few elements can be noticed from Fig. 8 and 9 :

1. There is no semi-annual signal in the data that have been analyzed.
2. The amplitudes of the annual signals are generally larger than what is theoretically expected. Apparently, LASER-CSR and DORIS-GRGS are the only time series that could fit the theory in terms of amplitude of the annual signal. And to a smaller extend, the GPS-JPL and DORIS-IGN combined solution is in much better agreement with theory than original series.
3. The large distribution of phases (Fig. 8) suggests to keep a cautious eye on the presented results.
4. The discrepancies in the Z-component has to be related to the Z-component of Space Geodesy reference frame realization which is noisier than any other direction, since tracking networks are non-uniformly distributed over the Earth.

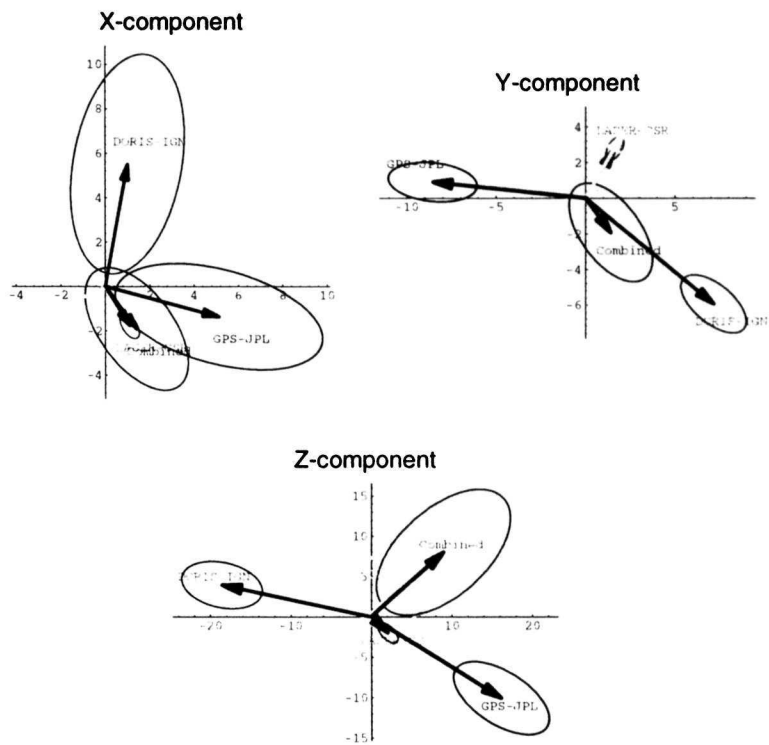


Figure 8: Annual signals

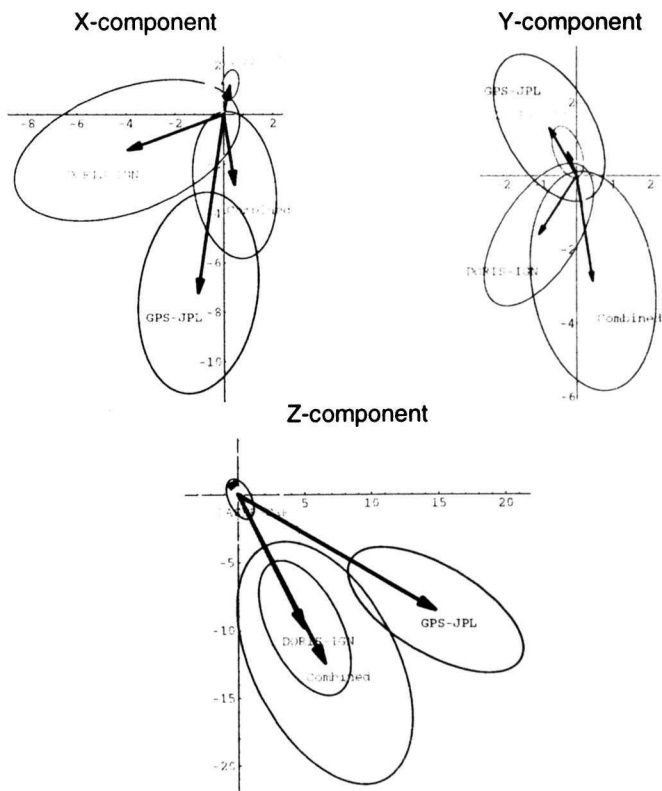


Figure 9: Semi-annual signals

5. There is still a doubt about the convention used by analysis centers : in which direction the position vector of geocenter is? For sets of coordinates combination, the convention is as the following:

$$\begin{pmatrix} x_G \\ y_G \\ z_G \end{pmatrix} = \overrightarrow{OG} \quad (4)$$

where (x_G, y_G, z_G) are the components of geocenter in the given time series, O is the origin of the frame of reference, and G is the instantaneous geocenter.

Until now, the time series were studied in a very narrow part of their spectrum. A wavelet analysis has then been carried out in order to check if some different signals were detectable. The analysis was restricted to the Y-component, because it is the one which seems to be most promising and the results are quite coherent with what has already been explained.

Wavelet transform in amplitude is presented in Fig. 10. It is remarkable to see that apart from the annual signal, everything else is nothing but noise in all this time series. This fact has to be moderated for the GPS-JPL series, as the apparent period seems to be about 8 months. Nevertheless, there are only 20 months of data which gives an idea of the difficulty to find a 12-months period. It must also be emphasized that the combination of DORIS-IGN and JPL-GPS is again a 12-month signal which shows the interest of such a combination and emphasise the relevance of the method.

Fig. 11 shows, as an example of problems that still remain, the wavelet transform of LASER-CSR X and Z-components. As can be seen, the Z-component is no longer a one year period signal.

6 CONCLUSION

The results obtained by Space Geodesy techniques in terms of geocenter monitoring seems to be encouraging : an annual signal is clearly visible in all the time series. Nevertheless, the amplitudes and phases are not coherent enough to conclude that the detected signal is a common real physical signal. The theory predicts (Dong et al., 1997; Chao and O'Connor, 1988) an amplitude of the annual signal much smaller than the centimeter level. This theory is based upon atmosphere, ground and ocean water redistributions analysis. Space techniques have demonstrated the potential they have in determining geocenter motion (Watkins and Eanes, 1993; Vigue et al., 1992). This capability has to be crosschecked and until now, there remain some inconsistencies between individual determinations that might be due to the use of inconsistent physical models : as a matter of fact, many of the models used to reduce Space Geodesy observations might have an annual signature (Ocean and Earth tide models, troposphere, ...), and before asking whether or not Space Geodesy is capable to detect Geocenter motion, one should study to which extent the discrepancies between the physical models used to reduce the data can disturb the geocenter determinations. The results presented here are promising, but the main task that has to be carried out is to unify the physical models and then, the convergence of the results should derive.

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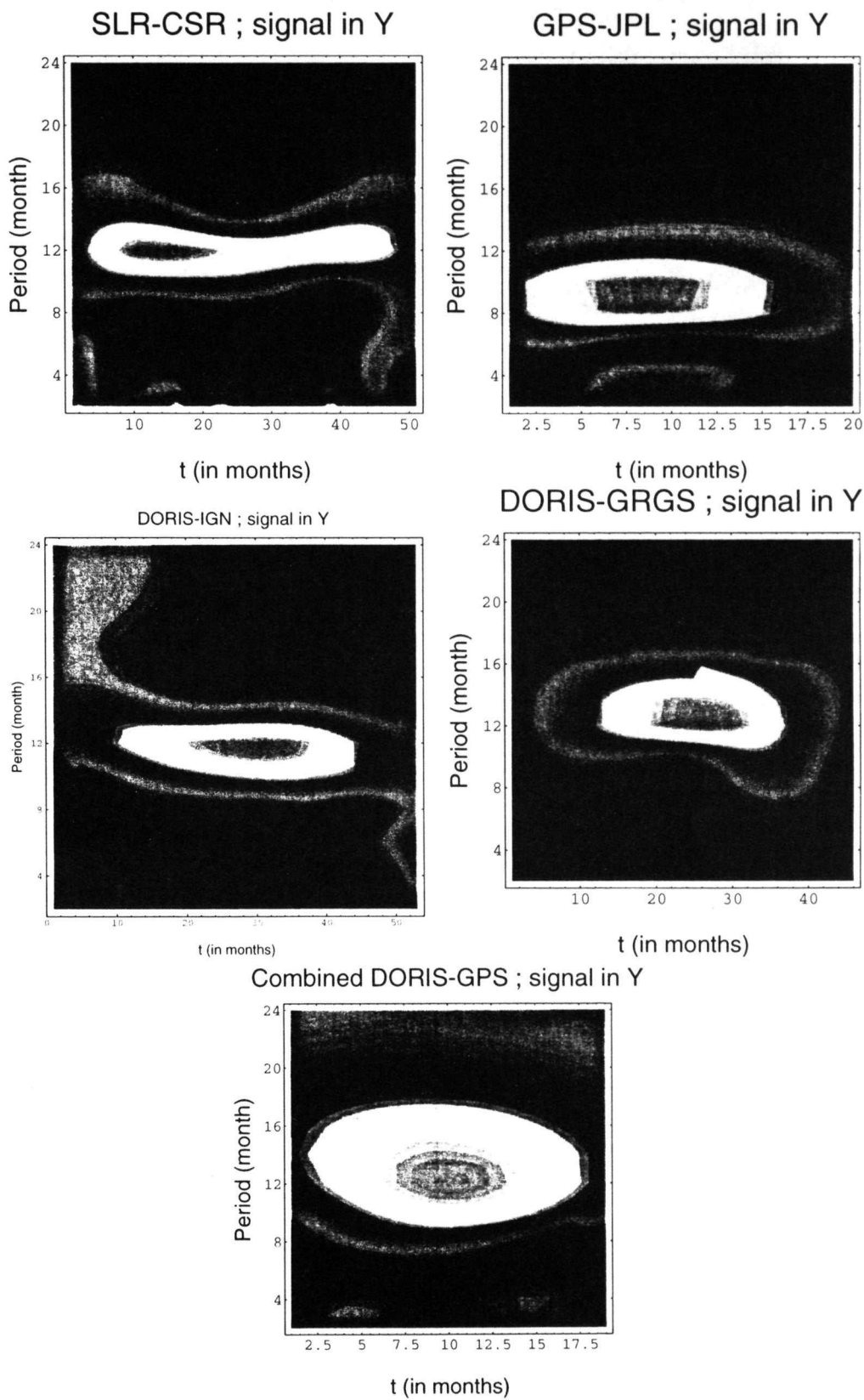


Figure 10: Y-component wavelet analysis

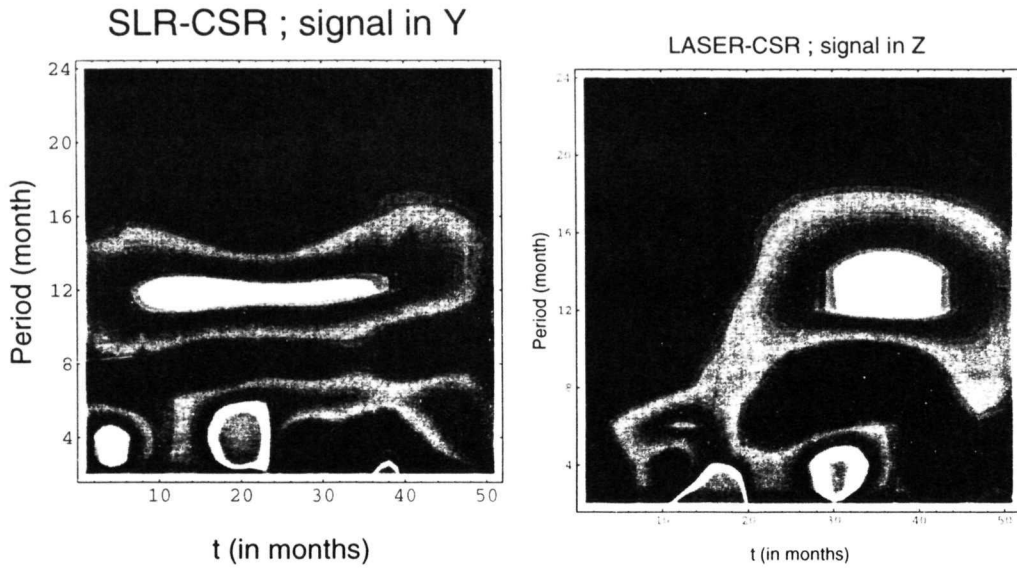


Figure 11: X and Z component of LASER-CSR geocenter

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MONITORING GEOCENTER AND SCALE VARIATIONS USING DORIS DATA: MONTHLY AND WEEKLY COMPARISONS TOWARD ITRF REFERENCES

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INTRODUCTION

Since 1992, the Institut Géographique National is using the GIPSY/OASIS II software, developed by the Jet Propulsion Laboratory, for DORIS data processing [Willis et al, 1994]. Main applications are precise geodetic positioning for the stations of the ground tracking network, precise orbit determination (Topex/Poseidon) and also polar motion monitoring in the scope of the International Earth Rotation Service (IERS) [Willis 1996a; Willis 1997].

Within the Geocenter campaign organized by the IERS, IGN has derived monthly and weekly coordinates data sets from DORIS data analysis than can be used to estimate possible variations in location of the geocenter. Several authors [Stolz 1976; Dong 1997] have shown, that due to geophysical changes in the geographical distribution of the Earth masses, the Earth center of mass should have some small variations mostly at an annual period.

The goal of this paper is to present the results obtained at IGN during this IERS Geocenter campaign, both for geocenter variations and also for scale factor variability.

DESCRIPTION OF THE DORIS DATA ANALYSIS

It must first be noted that the DORIS data are more inhomogeneous than for other space techniques, such as GPS or even SLR data. There is not a « DORIS constellation » of satellites as it exists for GPS. There are in fact several satellites carrying a DORIS receiver on-board, but the number of these satellites is changing in time, as described in the table below. There are then periods of time for which 3 DORIS satellites are available (March 1994 to September 1996) and other periods for which only one or two satellites are available. We should keep this in mind while analyzing the next results. It is not surprising that the results themselves will show some improvement during multisatellites period, as more data will be available for each DORIS tracking stations.

Period	DORIS satellites	Comments
April to June 1990	SPOT2	
January to March 1992	SPOT2	
January 1993 - February 1994	TOPEX	SPOT2 data existing but not yet available to IERS
March 1994 - September 1996	SPOT2+SPOT3+TOPEX	
October 1996 - December 1997	SPOT2+TOPEX	SPOT3 satellite lost in September 1996

Table 1: Description of the DORIS data analysed

For all the following DORIS processing, the GIPSY/OASIS II software, developed at JPL was used. One of its particularity is to use a filtering approach of the data, making it extremely easy to estimate stations coordinates in a so-called « free-network approach » [Heflin 1998]. In this case, all stations coordinates are estimated simultaneously with the orbital parameters and all the other parameters (Earth orientation parameters, tropospheric corrections, clock drifts offsets). In order to make the estimation problem non-singular, a priori standard deviation information are added to the filtering sequence for the stations coordinates parameters.

However, these a priori constraints are rather loose (typically 100 m for all three components). The terrestrial reference frame of the computations is then only loosely known. Daily computations are done for all DORIS satellites.

When two or more satellites are available, all data are processed in the same runs, making full profit of common parameters. This imposes that all common parameters have the same estimated value. This is true of course for external parameters such as the Earth orientation parameters (polar motion and UT1 - UTC rate). But this gives also additional constraints to parameters such as the tropospheric zenith delay. Even if the passes of the different satellites are not exactly simultaneous, this adds some constraint between these parameters, as we impose a time-dependant constraint on this parameter due to the rather stable nature of the troposphere [Willis et al, 1998a].

In order to express the stations coordinates results in a well defined and well maintained in time reference frame, several steps are required, involving different processing techniques [Willis 1996; Dorie, 1997]:

- **combining** the daily DORIS coordinates data sets into weekly, monthly (or even longer period of time) using the full covariance matrix of the positions estimates.
- **projecting** the weekly (resp. monthly) global coordinates data sets solutions. This procedure projects the full covariance matrix in a terrestrial reference frame for which the variance is minimum. It does not affect the coordinates of the stations themselves but only their estimated standard deviations, making them smaller (from about 10 m to a few mm), removing indetermination due to the fuzzy definition of the underlying terrestrial reference frame.
- **transforming** the obtained projected solutions in a unique terrestrial reference frame, realized by a global data set of stations coordinates and velocities used as reference, by estimating a 7-parameter transformation. It must be noted that the precision of the results is limited by two different sources of errors: the error coming from the DORIS estimation itself (limited by the number of DORIS measurements available, the DORIS data noise and the possible mismodelling errors in the DORIS measurements), but also from the reference itself which cannot be anymore considered as perfect at these levels of precision.

It must also be noted that for this transformation, the reference solution has to be propagated in time to the mean epoch of the DORIS observations as all stations move towards one another due to geophysical considerations (plate tectonic). Any error in the velocity field of the reference solution will then propagate in the result of this transformation, making it difficult to differentiate between errors coming from the DORIS free-network solution itself (free of any terrestrial reference frame error by construction) and errors coming from the reference.

The results of this last operation provide simultaneously the coordinates (and its associated full-covariance matrix) and also the estimated 7-parameters of the transformation for which we will focus our discussion in this paper.

The 7 parameters correspond to:

- **3 translations** (difference between the realized origin of the system that can be assimilated to the instantaneous center of mass of the Earth towards a conventional origin of the frame given in the reference),
- **1 scale factor** (ratio between the realization of the meter value and its conventional value provided in the reference),
- **3 rotations** (that are in a certain sense conventional) and which will not be discussed in this paper.

The first 4 parameters (translations and scale) have then a physical significance as they can provide information on possible physical variations of the geocenter (due to temporal changes in the Earth mass distribution) and also in the realization of the unit of length (meter) that is usually biased by unmodelled effects such as propagation errors (ionospheric corrections).

The transformation operation also provides a estimate of the goodness of the fit: the root mean square (RMS) of the stations coordinates. Figure 1 shows the evolution in time of this statistical estimator.

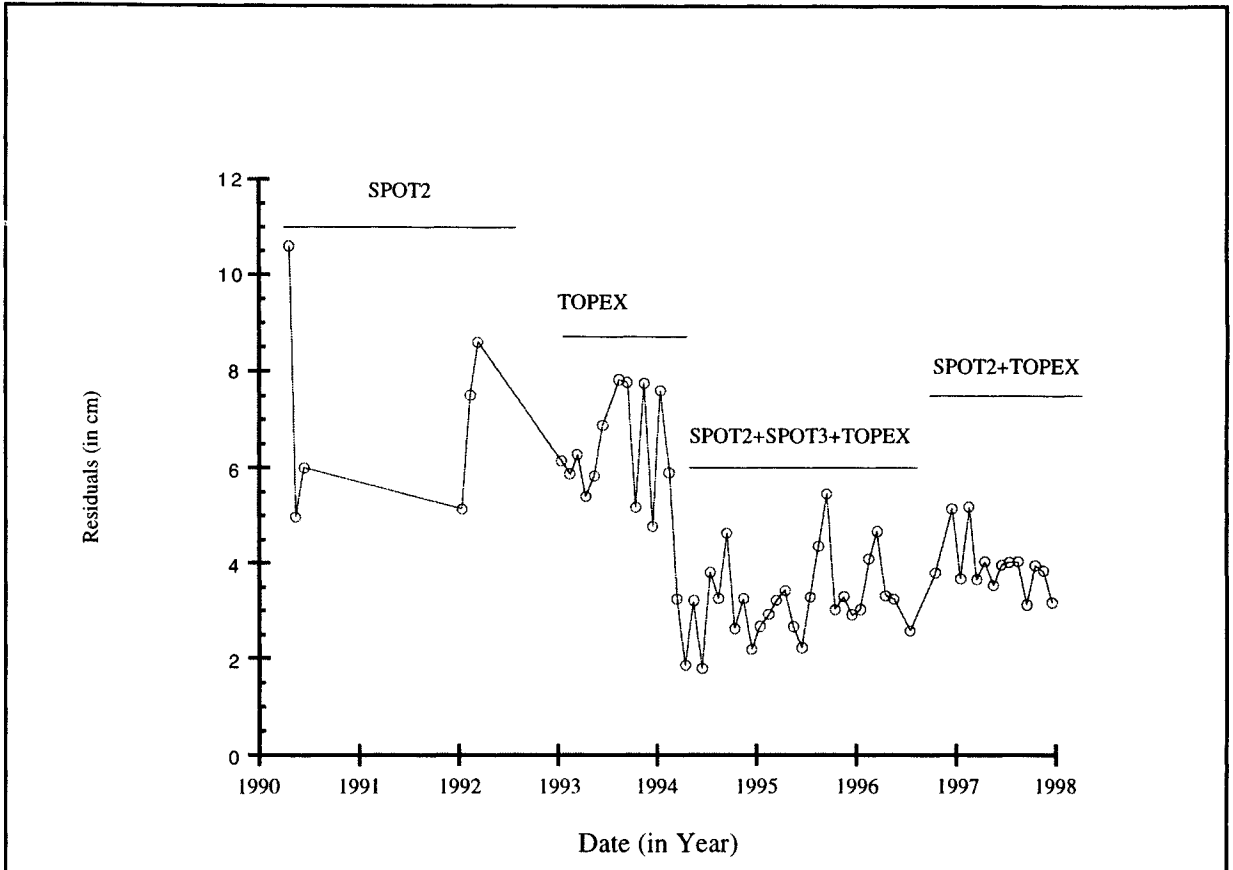


Figure 1: Monthly DORIS stations coordinates residuals (towards DORIS/IGN reference IGN98D01)

In this comparison, we have used our own DORIS-derived solutions transformed in rotation only to be expressed in the ITRF96 reference frame (IGN98D01 DORIS solution presently submitted to the IERS Central Bureau for the ITRF97 realization).

Several important results can already be obtained from this single plot. First of all, the number of available satellite clearly improves the consistency of the results. The first months before March 1994 corresponding to only one satellite (SPOT2 and then TOPEX/POSEIDON) are effectively not as well consistent with the reference as the period corresponding to the 3-satellite period (March 1994 - August 1996, see table 1). On the other hand, the period after August 1996 corresponding to a dual satellite mode after the loss of the SPOT3 satellite can be considered as an in-between result between those two extremes.

In figure 1, we can also see a degradation in time during the 3 satellite period. This is certainly due to possible errors (or imprecisions due to the lack of long-term DORIS data history for some tracking station) in the DORIS velocities given in the reference. As this reference was established using all the DORIS data set available, the best coordinates can be obtained for the mean observation time of the stations. Before 1990 and after 1996 (last epoch for which some DORIS data was included in the ITRF96 realization [Boucher et al, 1998]), the coordinates are

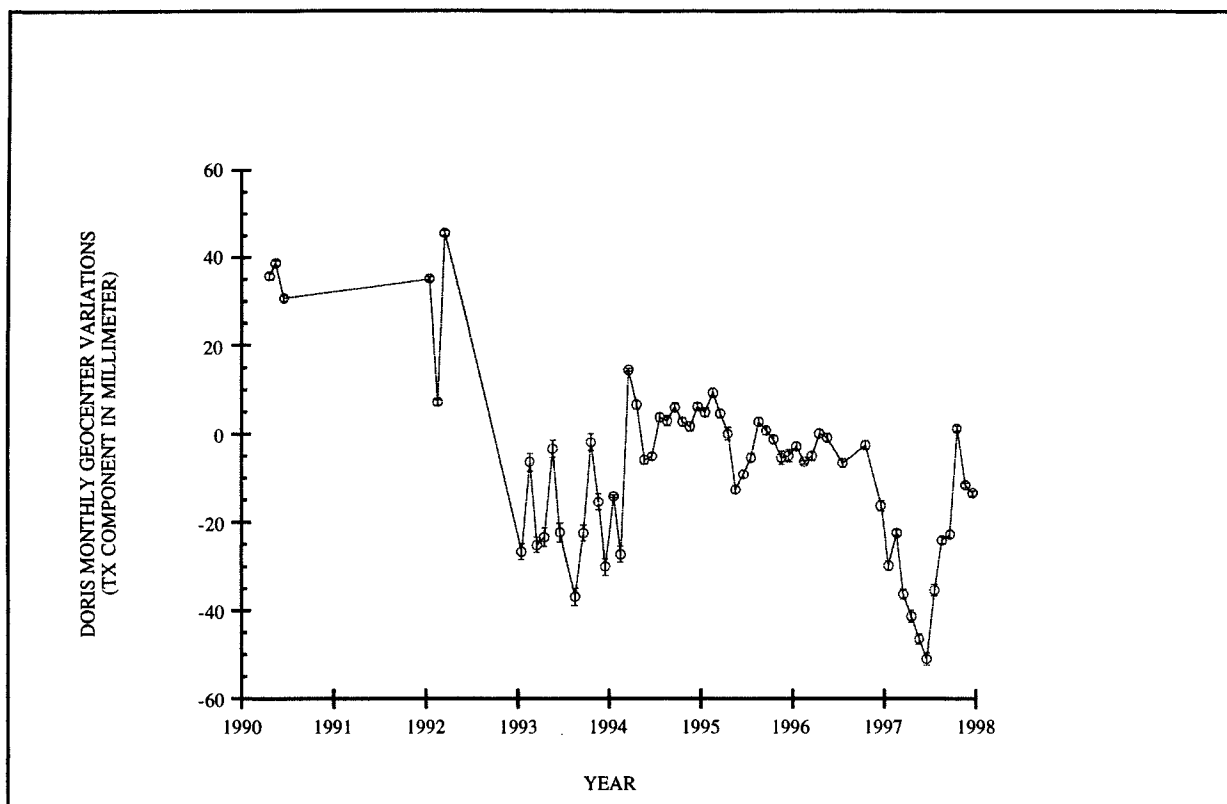


Figure 2: Monthly geocenter variations (TX component)

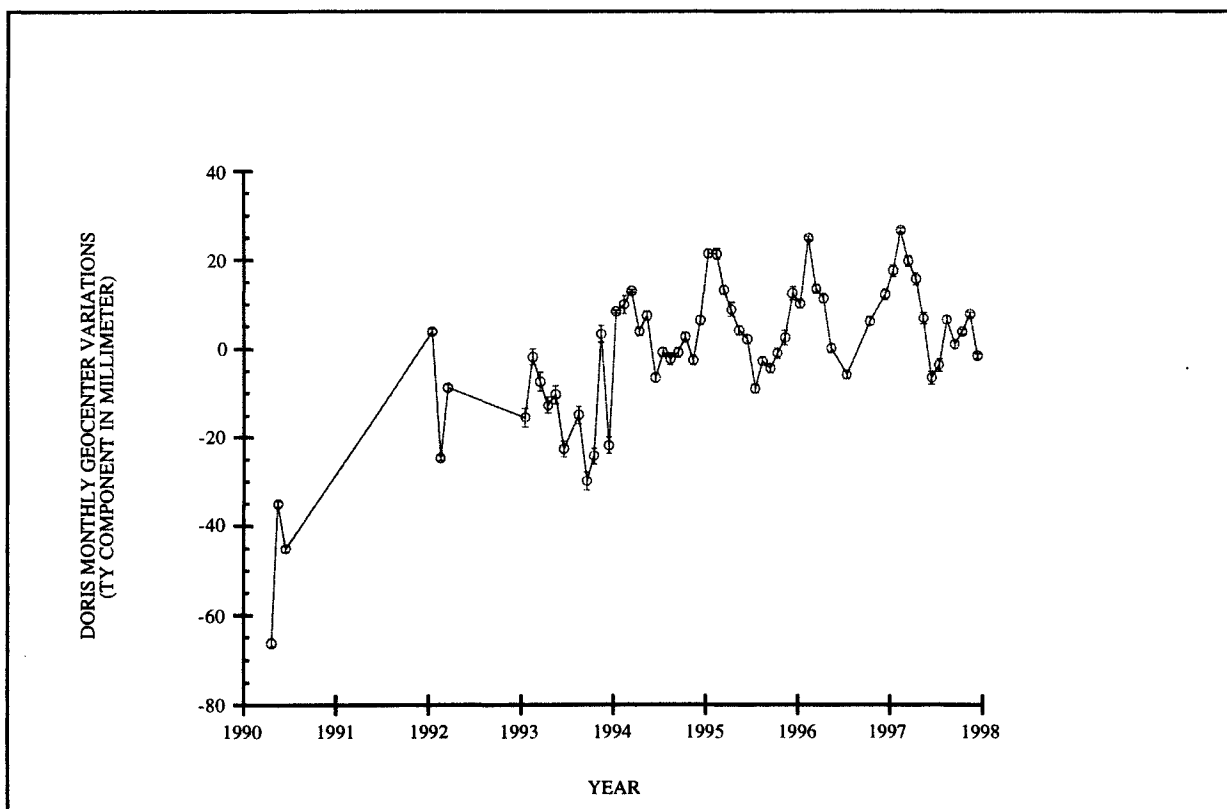


Figure 3: Monthly geocenter variations (TY component)

in fact extrapolated from the DORIS data and their accuracy is more and more affected by the reliability of the velocities given in the reference file.

The gaps that can be seen in this plots correspond to data that are not yet available to the DORIS/IERS analysis groups. In fact, these data exist and for technical reasons has not yet been formatted and distributed to the IERS groups. In the future, it is expected to get a complete series of measurements that could then lead to a continuous time series from January 1990.

No bias in X,Y or Z are visible for these (internal) comparisons.

MONTHLY GEOCENTER VARIATIONS

In order to give possible intercomparisons with other space techniques within the IERS geocenter campaign, DORIS monthly solutions were obtained and compared toward and ITRF reference [Boucher et al, 1994; 1996; 1997; 1998] . In fact, all available DORIS/IERS data were processed and not only the data during the period selected for the IERS geocenter campaign.

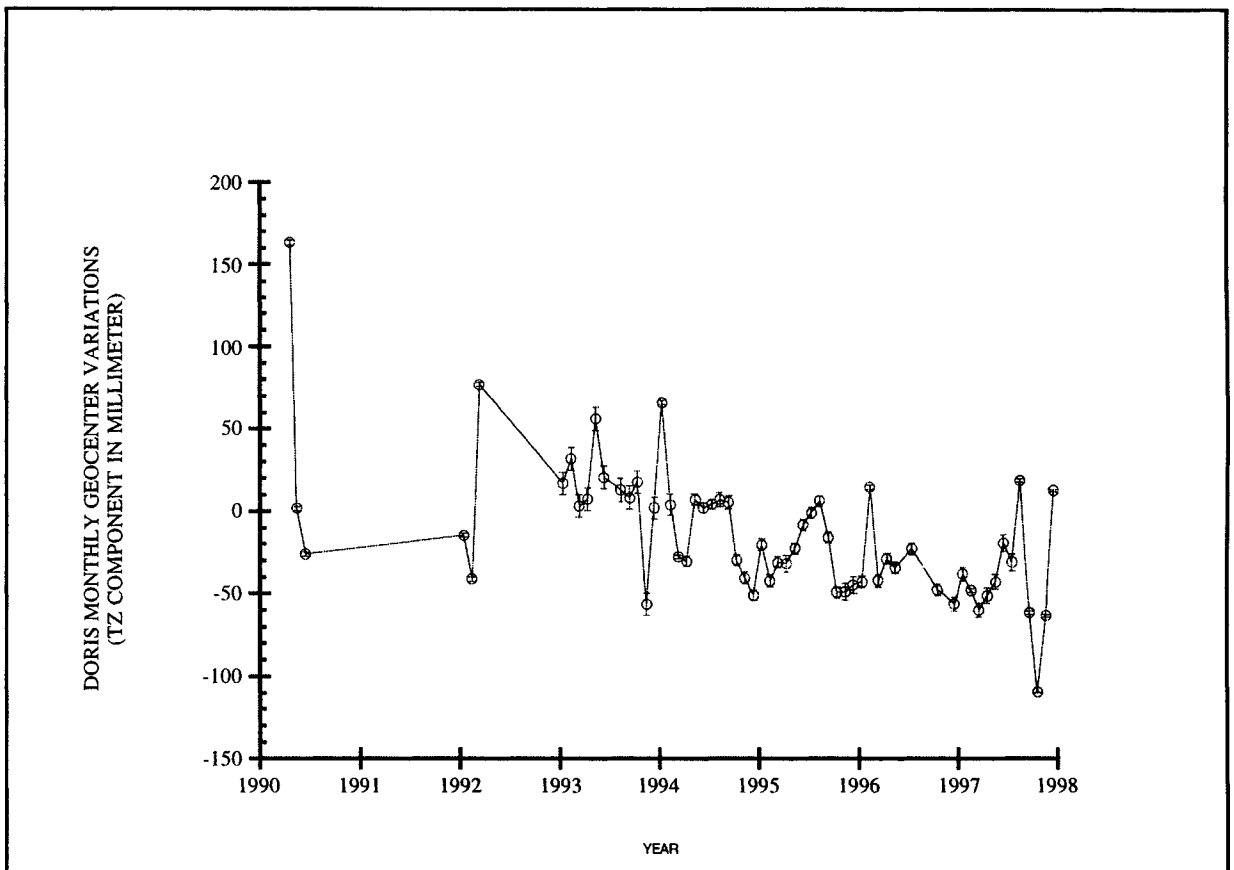


Figure 4: Monthly geocenter variations (TZ component)

Figure 2 to 4 shows results obtained for the geocenter variations in the 3 components X, Y and Z. In these plots, it is clear that systematic biases can be found between 1 and 3 satellites period. During the 3 satellite period, results seem to be less noisy and appear to show an annual signal. Curiously, the Y component seem to show a drift also that is probably coming from the noisier 1990 SPOT2 data at the start of the observation period. The Z component show variations with a larger amplitude as it is often the case in satellite geodesy.

WEEKLY GEOCENTER VARIATIONS

As a test, we also derive weekly DORIS solutions for test purposes [Willis et al 1998]. To be compatible with the equivalent GPS weekly series derived from the IGS (International

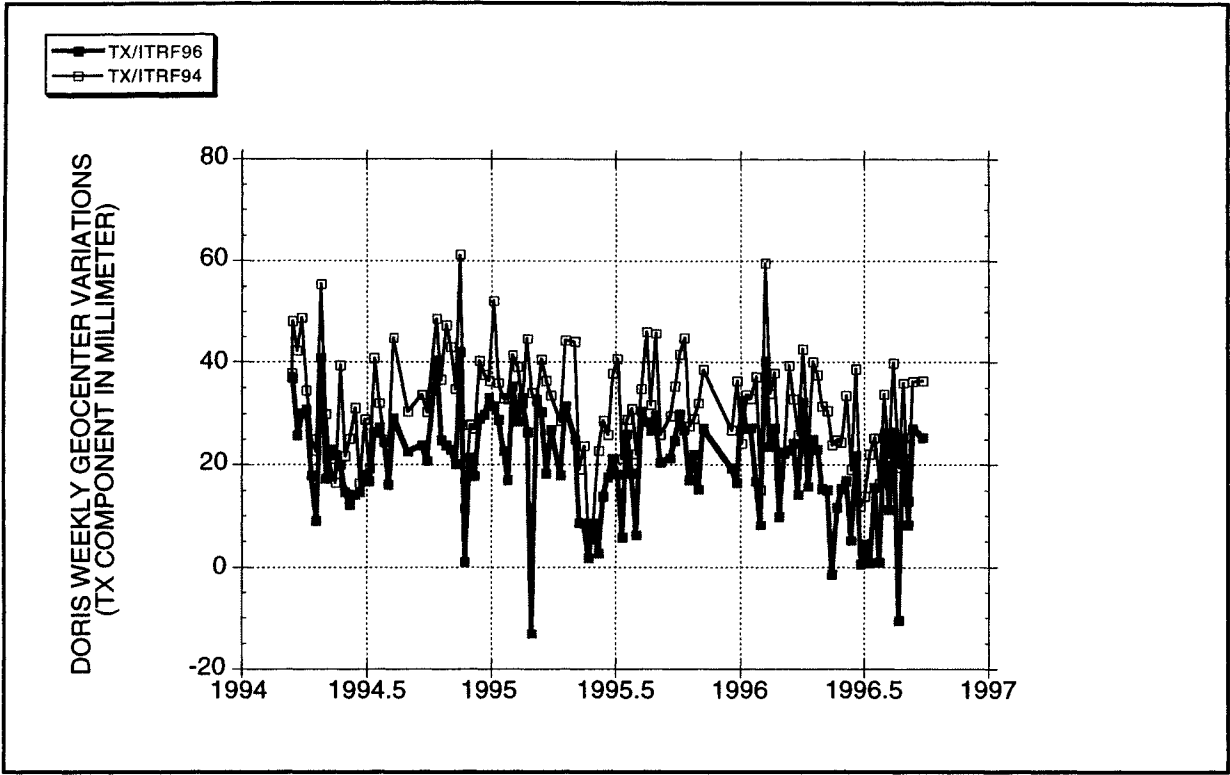


Figure 5: Weekly geocenter variations (TX component) compared to ITRF94 and ITRF96 references

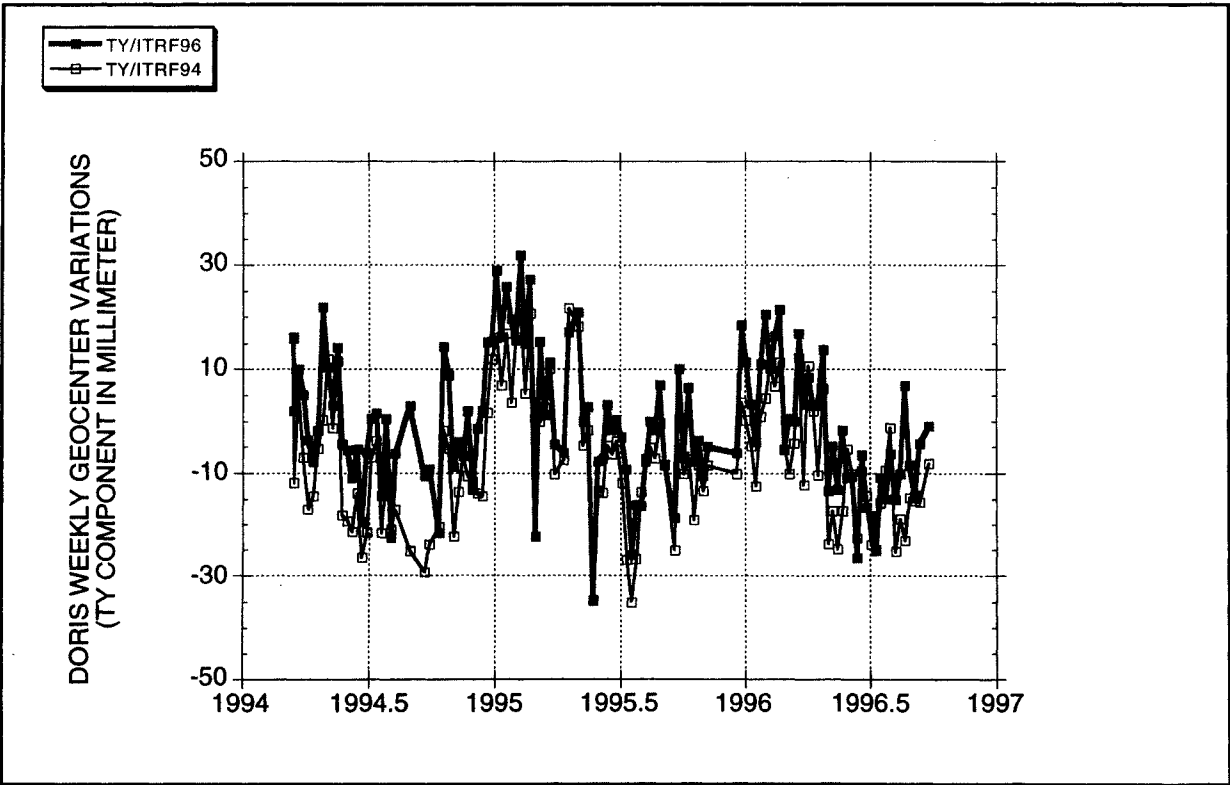


Figure 6: Weekly geocenter variations (TY component) compared to ITRF94 and ITRF96 references

GPS Service [Beutler et al, 1995]) groups, the week conventionnaly starts on a sunday and finishes on the following saturday. It is also expected that these weekly time series of DORIS derived coordinates could be used in the future, in combination with these already available IGS/GPS weekly time series to ITRF combinations.

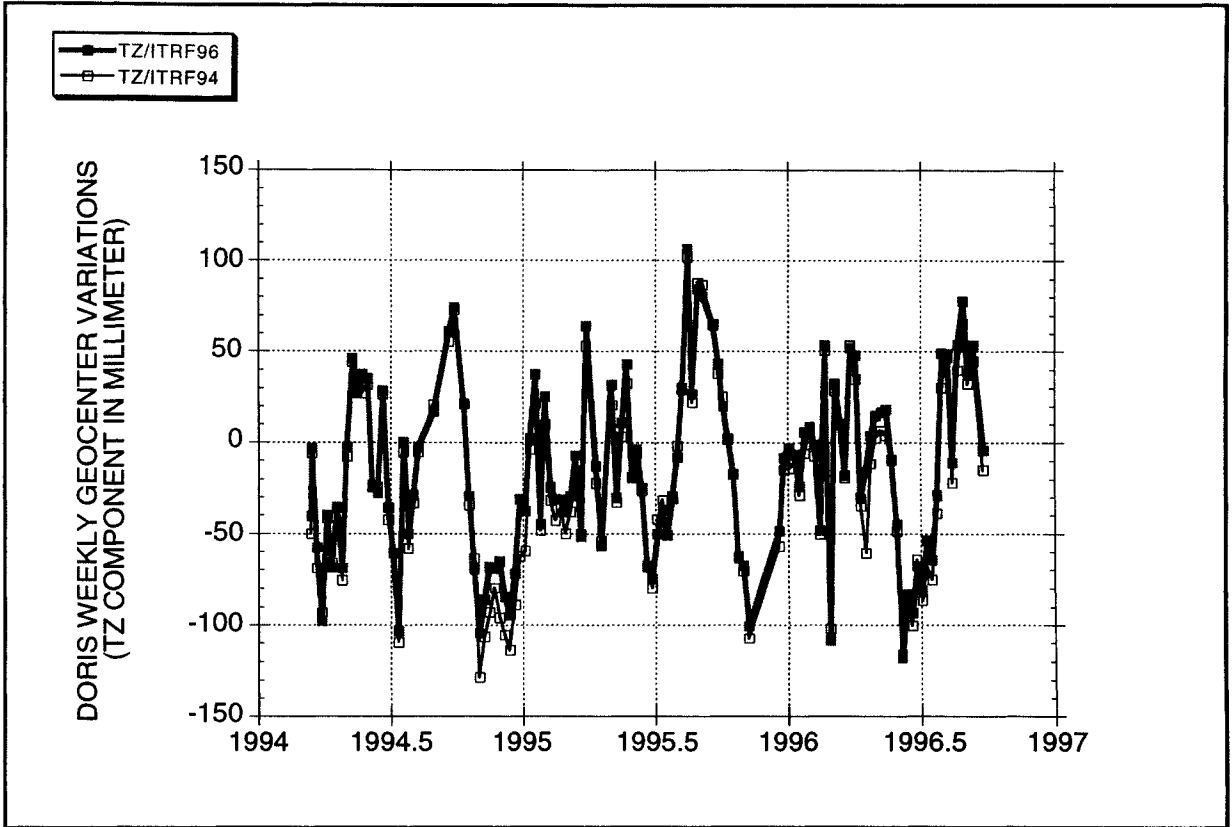


Figure 7: Weekly geocenter variations (TZ component) compared to ITRF94 and ITRF96 references

Figure 5 to 7 shows weekly geocenter variations determined with DORIS during the 3 satellite period. As it was also shown for monthly solutions, the Z-component is noisier than the other 2 component X and Y.

By opposition with the monthly comparisons for which we have compared our monthly results with our own DORIS-derived reference frame solution (IGN98D01), we have tried to compared our weekly solutions directly to the ITRF reference. In order to look for possible errors in the reference itself, we have done in fact these comparisons twice (toward the ITRF94 reference and towards the ITRF96 reference).

Figure 5 shows a possible systematic error in the X translation of about 2 to 3 cm (see also table 2). This bias is curently found in all our results and seem to come from a systemetic offset found in the UTCSR and IGN solutions (using 2 different software, GIPSY/OASIS and respectively UTOPIA). There is no detectable bias for the Y component and the Z component is too noisy to make any further investigation. No really convincing explanation has been found yet for this effect (larger than the estimated variations of the geocenter due to geophysical phenomenon).

From these plots an annual signal can be seen and is more visible in the Y component which is noisier. However the data span of observations seem really too limited to try to estimate a meaningful amplitude or even phase of this signal.

Table 2 summarizes the bias observed toward the ITRF94 and ITRF96 solutions. The standard deviation of the results among this mean is smaller for ITRF96 compared to ITRF94, showing that ITRF96 is more compatible with our new DORIS solution.

Reference	TX (bias) (in mm)	TX (standard deviation) (in mm)	TY (bias) (in mm)	TY (standard deviation) (in mm)	TZ (bias) (in mm)	TZ (standard deviation) (in mm)
ITRF94	31.9	10.4	-7.7	12.4	-22.1	50.3
ITRF96	20.4	10.3	-0.6	13.0	-15.8	49.0

Table 2: Weekly translations comparisons between DORIS solutions and different ITRF realizations (ITRF94 and ITRF96)

MONTHLY SCALE FACTOR VARIATIONS

The stability of the scale is also an important parameter that needs to be monitor as it is an estimator of the stability of realization of the unit of length (meter SI). Figure 8 shows the variations observed in the monthly scale using the DORIS data.

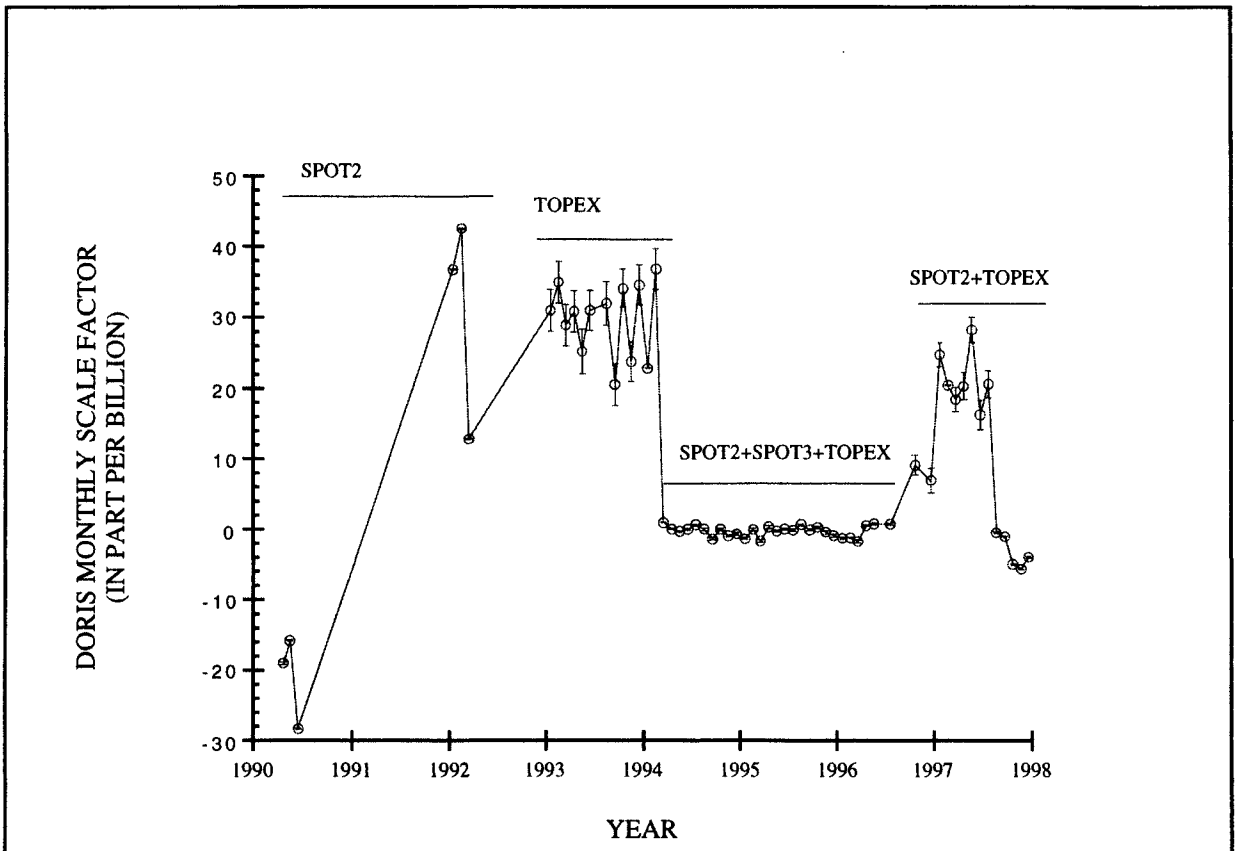


Figure 8: Monthly scale factor variations compared to ITRF94 and ITRF96 references

One more time, it is obvious from this plot that the number of available DORIS satellite is a critical issue to get precise scientific results from this system. It can be seen that with only one satellite, variations can be found at levels up to 40 ppb (part per billion), equivalent to a global height increase of all the stations of 24 cm! However, when 3 satellites are available, such as in the 1994-1996 period, variations are much less, up to 1 to 2 ppb, equivalent to 5 to 10 mm in height variations.

This plot shows also a clear anti-correlation with the TX monthly geocenter variations. This point is not completely well understood and is presently attributed to a possible error for one (or several) tracking stations coordinates. Further investigations are obviously needed to clarify and understand this effect often called « network effect ».

WEEKLY SCALE FACTOR VARIATIONS

The same study was applied to the weekly solutions, but only in the 1994-1996 period for which 3 DORIS satellites are constantly available. It can be seen that variations are now extremely small (up to 4 ppb, equivalent to 2,4 cm in height).

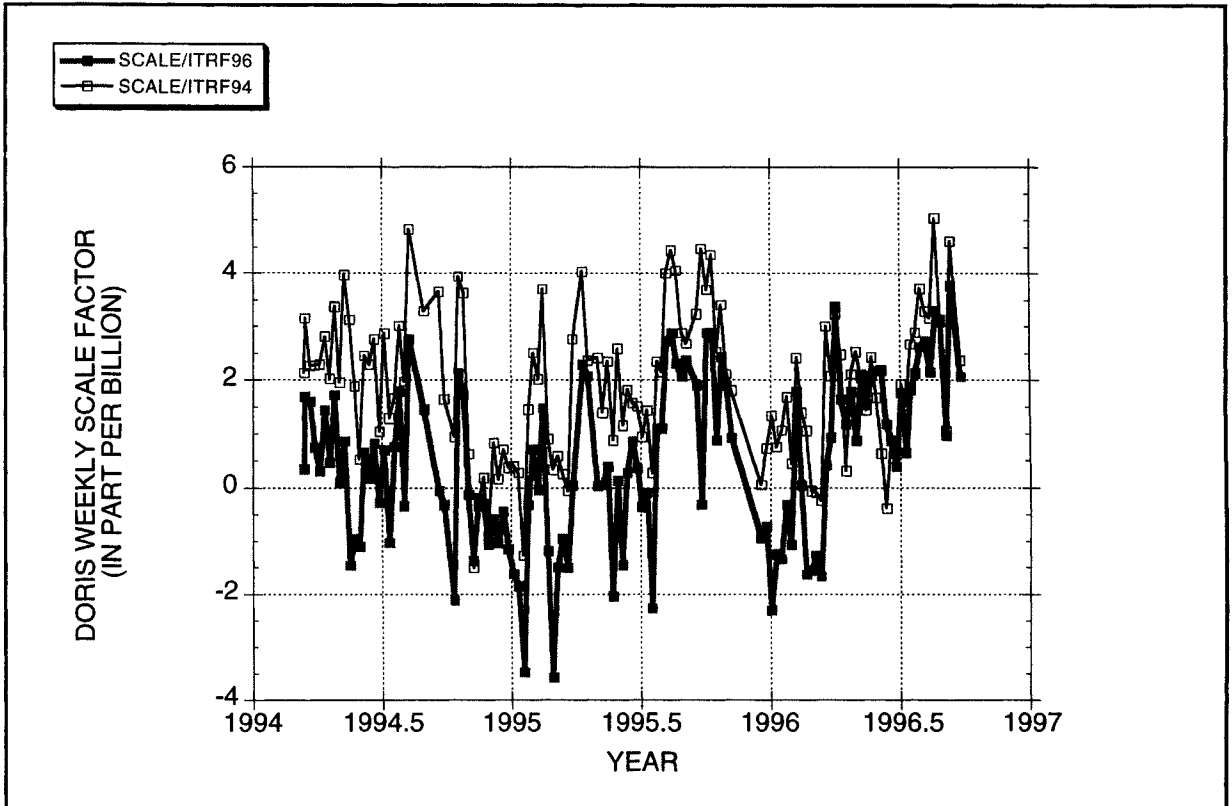


Figure 9 : Weekly scale factor variations compared to ITRF94 and ITRF96 references

To be consistent, we have compared this scale to the ITRF94 and also to the ITRF96 scale (which is supposed to be the same by construction). It can be seen that the two comparisons are very similar (by oppositions to the results found for the geocenter determination in this paper).

A annual signal is also visible. However, the data span seems to be too limited (less than two year) to estimate significant phase and amplitude parameter of the signal.

Reference	Scale (bias) (in ppb)	Scale (standard deviation) (in ppb)
ITRF94	1.9	1.4
ITRF96	0.5	1.5

Table 3: Scale factor comparisons between DORIS solutions and different ITRF realizations (ITRF94 and ITRF96)

The scale is well aligned with the ITRF scale (it is even true for the latest ITRF96 realization) showing no systematic difference in time at the 1 ppb level of precision. Table 3 summarizes these results in term of systematic bias and standard deviation towards this mean.

IMPORTANCE OF GEOCENTER VARIATIONS AND SCALE FOR DORIS DATA PROCESSING

Main objectives of DORIS data processing are precise orbit computation and precise geodetic positioning of the tracking network.

In the case of precise orbit determination (for possible scientific uses in satellite altimetry, eg Topex/Poseidon mission), an error in the origin of the frame or in the scale would propagate in the orbit parameters. This would create systematic errors for future oceanographic investigations. Presently, the variations shown in this paper seem to be small (few mm for the geocenter and a couple of part per billion for the scale). However, future altimetric mission, such as the JASON mission have a more drastic goal of 1-cm accuracy for the orbit determination. In this case, all the above errors should be taken into account by providing a realistic model which is one of the scientific goals of the IERS Geocenter campaign.

On the other hand, these variations affect also the geodetic positioning results. In the combination of the daily coordinate data sets results, it is assumed in the model that the origin is unique. This point is not true anymore if we assume that the origin of the frame in the daily solution is related to the center of mass which have some seasonal variations towards a conventional origin. It would then be important in the future to have access to a new model, correction this effect in the DORIS measurement, allowing to express naturally the daily coordinates results (reference frame realization) toward a conventional origin. However, as it is also shown in this paper, DORIS derived geocenter and scale variations show an annual signal but also show some other systematic effects that would not be corrected by such a model. Furthermore, it must also be proved that the variations seen using the DORIS system are coherent in amplitude and also in phase with the variations derived from other systems (SLR, GPS).

CONCLUSIONS

In conclusion, the DORIS system is able to provide useful information about possible variations of the geocenter. Results presented in this paper show that an annual signal can be visible in the DORIS results (monthly and weekly solutions). No semi-annual signal seems to be visible. However, when only one DORIS satellite was used, results are much more noisier showing the need for a real DORIS constellation of satellites (at least 3 or 4!). As several DORIS satellites should be launched in the next future (ENVISAT, JASON, SPOT5), it is then expected that these results will be confirmed and ameliorated soon.

On the other hand, the two IERS reference used in these tests (ITRF94 and ITRF96 realizations) show inconsistency at the 2-3 cm level for the X component of the origin. This result has been verified by other authors [Sillard 1998] and can probably be attributed to the lesser accuracy level of the ITRF94 solution, being the first ITRF realization to incorporate DORIS stations coordinates and velocities, the DORIS observation data span may not have been sufficient to obtain precise velocities estimates.

The periodic term of the geocenter variation is at the 1 cm level and then needs to be corrected in the future. Otherwise, DORIS results (monthly, weekly) would suffer from this mismodelling. This point is also true for global solution incorporating several months of DORIS solutions and should be treated with great care in the near future. It is expected that the IERS Geocenter campaign will help to define a reference model, at least for the annual variations of the geocenter.

Stability of the scale factor derived from the DORIS solutions is around 1-2 ppb, equivalent to a global indetermination of the heights of the DORIS tracking network of 5-10 mm. These

variations can certainly be explained from mismodelling in the ionospheric (or tropospheric) correction. However, the differences towards the ITRF94 and ITRF96 realization are extremely small are very much comparable with results obtained by otherspace techniques within the International Earth Rotation Service.

Even if these variations are extremely small (even smaller when more DORIS satellites are available), they need additionnal scientific investigation. As a matter of fact, such systematic errors in the scale factor would affect directly the estimated radial component of the orbit component. In the case of oceanographic mission (eg Topex/Poseïdon), this could then lead to noisier geodynamic data leading to less precise scientific products (mean sea level rise, ocean currents, tides,...).

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GEOCENTER VARIATIONS DERIVED FROM GPS DATA

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1. ESTIMATION METHOD

For a 14 months period (95.06.01 - 96.07.31) geocenter positions were solved in a two-step procedure: In a first step, only GPS data were used for orbit determination, with the station coordinates being treated as unknowns, yet with tight constraints (0.5 cm a priori sigma for 'core' stations, 5-10 cm or more for the other stations). In the second step, the geocenter correction was explicitly solved for by using the GPS orbits of step one as fixed, together with all other station coordinates. In order to avoid singularity, weak constraints were applied (10 m a priori sigma).

The theoretically possible explicit computation of geocenter corrections in one complete simultaneous adjustment was not carried out because the application of weak constraints leads to unstable solutions. Tests of this procedure with given 2 cm artificial geocenter variations led, due to the weak constraint, to recovered values of 1.7 cm, whereas with the two-step approach the recovered value was 1.9 cm. (To recover exactly 2 cm in the two-step method is not possible as well because the restituted orbit is affected by the constraint, too.)

2. MAJOR ERROR SOURCES

(a). *Error in GPS orbits.* Parameters like GM value, gravity model or third body model are sufficiently accurate. We have modified the GM value by 10^{-8} , and used the GRIM4 instead of the JGM3 gravity model. By doing so, the translation parameters of the orbit were changed only by less than 1 mm. By employing or neglecting models like an albedo model, solid earth tide model, or ocean tide model, the geocenter variation is also only insignificantly (by less than 1 mm) effected. As regards the solar radiation model, we solved the scales in x and z direction separately and afterwards used the same scale for these two directions with effects on the translation parameters of a few mm up to centimeter level. This indicates that potential mismodeling influencing the geocenter estimation might occur in connection with radiation pressure, especially when the satellites are located in the shadow. Regulatives as once-per-revolution empirical forces can be used to absorb this error. Applying an empirical force model or not can affect the orbit translation parameter (corresponding to geocenter estimation error) by a few cm up to 10 cm. Once applied, the effect of GPS orbit errors on the geocenter estimation is at a few mm level. The following is a typical example. Data of Oct. 24-26, 1995 were used to form two 2-day arcs. The empirical force model was utilized in these two solutions. Table 1 gives the overlap orbit differences.

Table 1. The overlap differences of two adjacent orbits.

Translation in x, y, z (m):	.006	-.001	.007										
scale (10-8):	-.03												
Rotation (x,y,z) (mas):	.0	.1	.1										
Overall rms difference (cm):	8												
RMS per Satellite (cm)													
sat	1	2	4	5	6	7	9	12	14	15	16	17	18
RMS	7	14	9	7	7	9	8	12	7	7	7	8	11
sat	19	20	21	22	23	24	25	26	27	28	29	31	
RMS	5	4	7	5	8	7	4	8	5	6	9	5	

(b). *Inaccuracy of station coordinates.* The estimated geocenter (gc) position is the actual gc position plus the common (mean weight) correction of the station coordinates. Assuming the models and observations being without errors and the approximate coordinates having inaccuracies dX , their influence on gc is

$$dGC = F(dX_j, j = 1, \dots, n) = \sum (p_j * dX_j)$$

with p acting as a weight factor. If the station combination and geometry do not change, dGC will be more or less constant. Its effect on the gc variation estimation is negligible. Actually, the station combination and with this the geometry change from time to time. In order to reduce this effect on gc, one should try to keep dX as small as possible. An error in the a-priori values of station velocity has a similar effect.

3. RESULTS AND DISCUSSION

Fig. 1 shows the time series of our solved geocenter variation from the two-step approach. Besides the annual and semi-annual periods, the spectral analysis given in Fig. 2 displays other periodicities. Peaks are visible at periods of about 140 days, 60-70 days, 20 days and 14 days. We solved the annual and semi-annual terms together with the linear trend (and constant term) from the series in Fig. 1. The results are given in Table 2. The second line for each component indicates the sigma of the corresponding solution. The amplitudes of both the annual and semi-annual terms are for all components at a few mm level. The sigmas of the amplitudes are around 1 mm. The phase results are, however, less reliable. The daily x and y geocenter components are estimated with a repeatability of better than 1.5 cm, for the z-component with better than 1.8 cm.

Using other techniques such as satellite laser ranging, the geocenter can be estimated with better repeatability, but those are 12-days or even monthly solutions. If we convert our solution into 12-days or monthly values, the repeatability is also at the few mm level. On the other hand, daily solutions are preferable because they contain more high-frequency information (e.g., 14-day period variations). GPS is presently the most suitable technique for daily geocenter estimations.

Comparing with the sigma, the trends in X and Y direction are significant. But bearing in mind that the data span used is less than two years, to distinguish the possible quasi long period terms (periods of at least several years) from linear trends is a question too intricate, although it is obvious that such trend and/or quasi-long period terms exist.

Table 2. Amplitude and phase of annual and semi-annual terms (phases in degree, amplitude in cm).

	rms	const	trend	amp (annu)	pha (annu)	amp (semi)	pha (semi)
X:	1.47	-0.226	-1.286	0.430	34.8	0.274	237.5
		0.070	0.138	0.092	12.0	0.088	18.8
Y:	1.39	1.684	-2.536	0.917	186.5	0.475	21.2
		0.066	0.130	0.088	5.2	0.085	10.0
Z:	1.80	-0.880	0.164	0.676	210.3	0.522	85.1
		0.086	0.169	0.113	9.3	0.107	12.2

Series of station positions are generated as by-products. The comparison of our station coordinates with ITRF96 at epoch 1996.0 is given in Table 3. The difference in height is larger than for the horizontal components, possibly because of incorrect information on the antenna height at some stations.

Table 3. Difference between ITRF 96 and GFZ_GC solution for common GPS Stations.

	H	N	E	DP	DX	DY	DZ
RMS [mm]	9.7	3.8	3.8	11.1	6.4	6.7	6.1
mean RMS = 6.6 mm							
Helmert transformation parameters							
dx =	.0028 m		± .0015 m				
dy =	-.0044 m		± .0015 m				
dz =	.0042 m		± .0014 m				
scale:	-.0033 D-06		± .0002 D-06				
rotz =	.00025 arcsec		± .00005				
roty =	-.00105 arcsec		± .00006				
rotx =	-.00030 arcsec		± .00006				

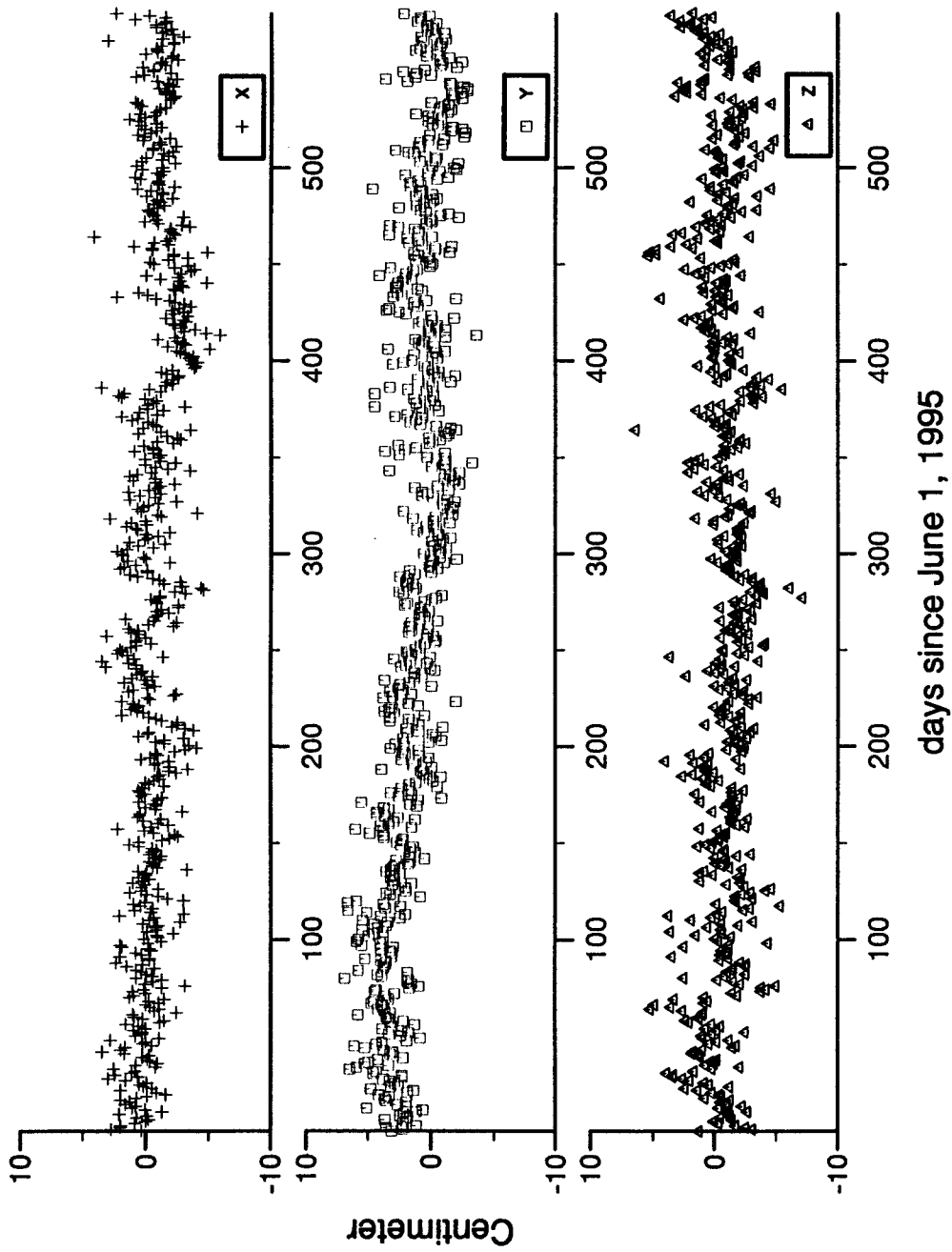


Fig.1 Daily geocenter variations

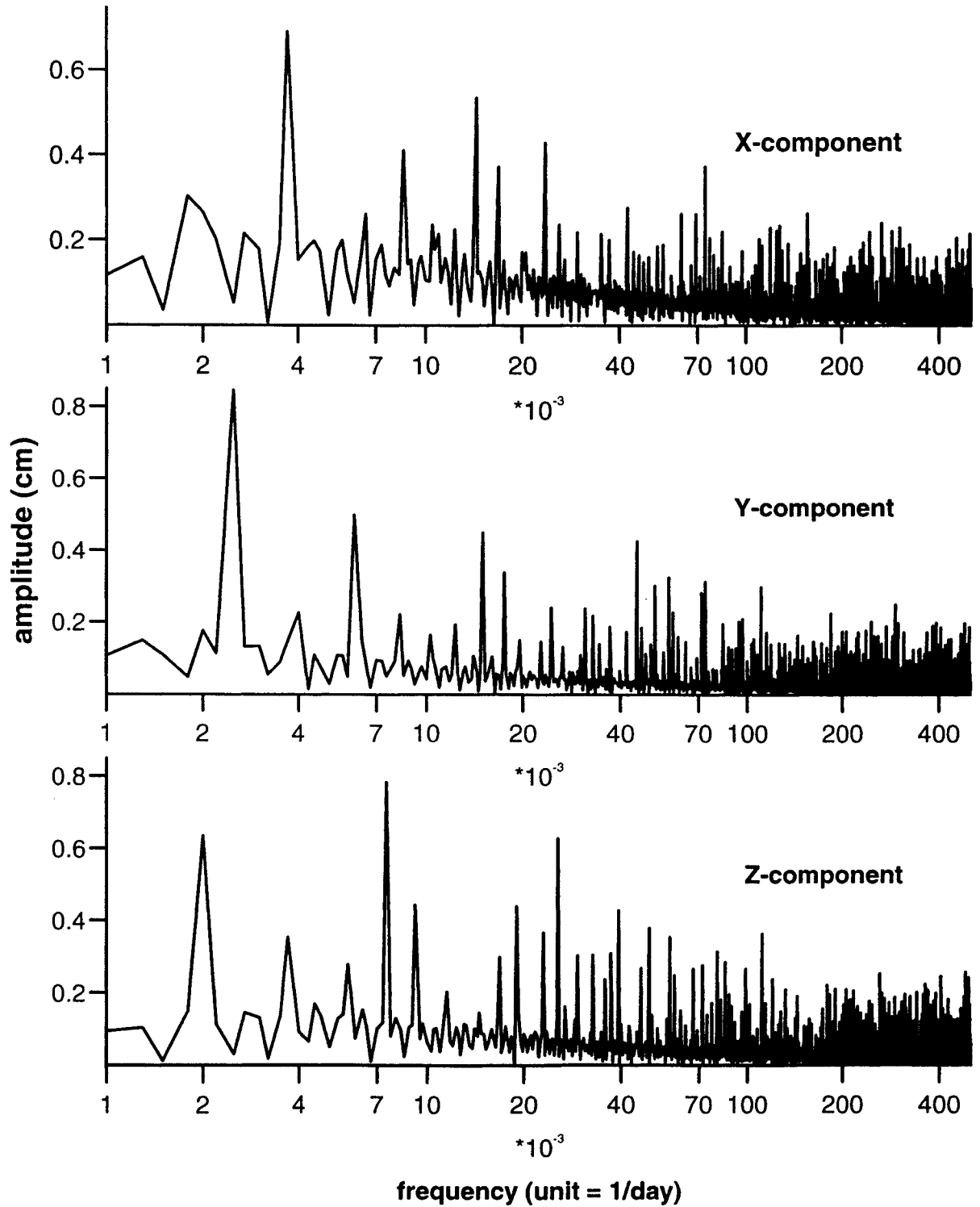


Fig.2 Spectrum of geocenter variations

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