

# Special Bureau for the Core

Tim Van Hoolst, Veronique Dehant

*Royal Observatory of Belgium, B-1180 Bruxelles, Belgium*

## 1 Introduction

The Special Bureau for the Core (SBC) is one of the eight Special Bureaus (SB's) of the Global Geophysical Fluids Center (GGFC), established by the International Earth Rotation Service (IERS) on January 1, 1998 to facilitate the link between the space geodetic and the geodynamic communities. Within the GGFC, the SBC is responsible for the research and data service activities related to the core and plays a role in stimulating and coordinating research on this topic. In particular, the SBC focuses on theoretical modeling and observations related to core structure and dynamics (including the geodynamo), and on inner core - outer core - mantle interactions.

Flow in the fluid outer core, and also motion of the inner core with respect to the outer core, can result in various geodetic phenomena observable from the Earth's surface or space. These phenomena include variations in the Earth's rotation and orientation, surface gravity changes, geocenter variations, and surface deformations. Although small, these variations can or could be observed by very precise space geodetic techniques. Observation of these effects then yields unique insight into the core, which can not be observed directly.

Since its creation in 1998, the SBC has set up a web site ([www.astro.oma.be/SBC/main.html](http://www.astro.oma.be/SBC/main.html)) as the central mechanism for providing services to the geophysical community. The web site contains documented model data on core flow and core angular momentum, and an extensive bibliography to support and facilitate core research. In addition, to provide some guidance into the vast literature in core dynamics, a description is given of the relevant theories and of the dynamical assumptions used for constructing the flow.

This position paper gives a brief overview of the various scientific issues and covers past and future activities of the SBC. We first describe in Sect. 2 the length-of-day variations, the main subject in this field, and treat the other effects in Sect. 3. SBC activities are described in Sect. 4.

## 2 Length-of-day variations

### 2.1 Core angular momentum variations

The fluid outer core is in constant motion, and changes in core angular momentum (CAM) are known to be related to length-of-day (LOD) variations of a few milliseconds at decadal time scales (see Fig. 1). These variations can very accurately be measured (uncertainty of about 0.02ms for daily LOD values) and were the main scientific reason behind the creation of the Special Bureau for the Core to stimulate, promote and aid in scientific investigations into the dynamics of the Earth's core by using Earth rotation variations.

The core has been recognized as the major component in explaining the lod variations at decadal scale since it was shown that the time-variations of parameters describing the geomagnetic field (such as the magnetic declination) are correlated with the variations of the LOD at these time scales. Furthermore, no other suitable reservoirs of angular momentum could be found. The core is considered to be able to exchange sufficient angular momentum with

## Core Angular Momentum (expressed in LOD unit)

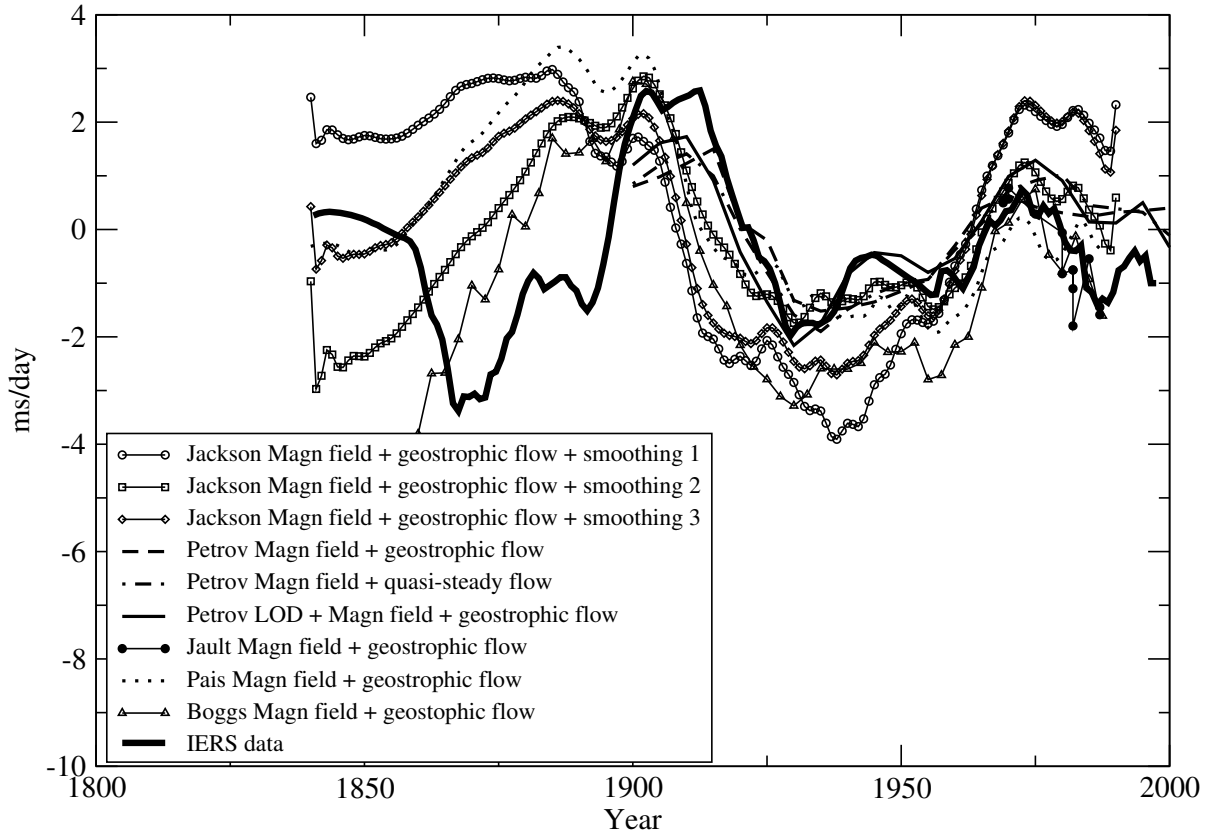


Figure 1: Length-of-day variations for various models and IERS observational LOD data. The data can be found on the SBC website.

the mantle. By using  $\vec{H}_m = C_m \vec{\Omega}$ , where  $\vec{H}_m$  is the angular momentum of the mantle, and  $C_m$  is the moment of inertia of the mantle, the change in mantle angular momentum can be estimated to be about  $1.3 \times 10^{26} \text{ kg m s}^{-1}$ . Because of the conservation of angular momentum of the core-mantle system, this also gives an order of magnitude for the core angular momentum change. Given the total core angular momentum of about  $6.5 \times 10^{32} \text{ kg m s}^{-1}$ , the core therefore changes its relative angular momentum by less than about  $10^{-5}$ .

No direct observations of the core flow exist as do for the atmosphere (and to a lesser extent for the oceans), and core flows are derived from variations in the poloidal magnetic field observed at the Earth's surface. These calculations, however, invoke several simplifying assumptions and hypotheses related, on the one hand, to the downward continuation of the surface geomagnetic field to the core-mantle boundary (CMB), and, on the other hand, to the determination of the horizontal flow in the superficial layer of the outer core from the magnetic induction equation. According to Holme (2002), the implicit assumption, in resolving the non-uniqueness in the core flow determination, that the flow is large scale may be the cause of the fact that all calculated flows are very similar. One may wonder then, whether these flows, although they very well model the geomagnetic secular variations, give a good representation of the true core flow. In this respect, the decadal LOD variations play an important role. Since the pioneering work of Jault et al. (1988), it has been shown that the core flows derived from the geomagnetic observation agree remarkably well with

the observed decadal LOD variations, adding to our confidence in the obtained core flows (see Fig. 1). To model the LOD variations, core angular momentum (CAM) is calculated from the the top core flow. This can be done since torsional oscillations govern the flow in the outer fluid core on decadal timescales (Braginsky 1970). These oscillations describe differential rigid rotations around the rotation axis of coaxial cylinders, for which magnetism provides the restoring force. Since core flow is then supposed to be constant on cylinders parallel to the rotation axis, velocities everywhere in the core can directly be derived from the velocities at the CMB, and thus the CAM can be derived.

## 2.2 Torques between core and mantle

Physically, the cause of angular momentum exchange between core and mantle is through coupling torques between core and mantle. These torques can excite torsional oscillations in the core. To explain the observed decadal LOD changes, the torque  $\vec{\Gamma}$  can be estimated from the change in angular momentum to be about  $\Gamma = C_m d\Omega/dt \approx 8 \times 10^{18} \text{Nm}$ . Four mechanisms have been suggested, but due to uncertainties in the flow and torque calculations, it has not been possible to definitely settle the relative importance of the different mechanisms.

1. The topographic torque is related to the effects of the fluid pressure on the boundary topography. The presence of bumps at the CMB has been suggested by both seismological studies in which refracted and internally reflected seismic waves at the CMB are used and convection studies in which the CMB topography deformations are computed from the buoyancy fluxes associated with density lateral heterogeneities in the mantle (seismic tomography). The efficiency of this mechanism is rather controversial, partly because of differences in the assumptions made in the calculation method (does the topography significantly affect the pattern of the flow?) and partly because of the uncertainties in the CMB topography (see Ponsar et al. 2002). The topography is thought to be less than 2 km according to Garcia and Souriau (2000), but about 3 km according to Sze and van der Hilst (2002). For these topographies, the torques are either somewhat too small (e.g. Kuang and Chao 2001) or too large (e.g. Jault and Le Mouél 1989).
2. The electromagnetic torque is generated by the Lorentz force on an electrically conducting layer at the base of the mantle and is associated with the magnetic field (and its variations). The magnetic torque is usually decomposed into poloidal and toroidal parts. The poloidal torque is connected to the poloidal part of the longitudinal component of the CMB magnetic field and its secular variation, which can be deduced from the observation of the magnetic field at the Earth's surface. The toroidal torque is connected to the toroidal part of the longitudinal component of the CMB magnetic field and its secular variation, which can be deduced from observations. Holme (1998) has shown that electromagnetic coupling can be large enough to explain the observed LOD variations, if the conductance of the deep mantle layer is high enough (conductance of  $10^8 \text{ S}$ ). Support for this hypothesis comes from nutation (see below). Such a layer could arise as a result of the cooling of the Earth. Cooling is associated with inner core growth and an increase in light element concentration, such as FeO, in the fluid outer core. These elements could be removed from the core and deposited as metallic solids at the base of the mantle (it is interesting to note here that an Fe-FeO system has a high melting temperature). Buffett et al. (2000) proposed that chemical reactions with mantle silicates can lead to silicate mineral deposits with interstitial liquid iron when excess light elements are created as a result of inner core growth.

3. The viscous torque is related to the viscosity of the fluid core at the core-mantle boundary and is generally believed to be small. However, if the top flow is turbulent, turbulent mixing could increase the coupling by orders of magnitude (Kuang and Chao 2002a)
4. The gravitational torque is related to the gravitational interaction between lateral variations in density within the fluid core and mantle and is small. The gravitational torque between the inner core and the mantle are, however, much larger and lock the rotation of the inner core to that of the mantle, if the inner core behaves elastically (Buffett 1996). LOD variations can then arise through electromagnetic coupling of torsional oscillations inside the fluid core with the inner core. The seismic observation of a differential rotation of the inner core has prompted some modifications to the locking (Buffett 1999), although this observation is controversial (Laske and Masters 2002). Recently, Mound and Buffett (2002) developed a similar inner core-outer core-mantle coupling scheme to explain observed LOD variations with periods of about six to seven years and an amplitude of about 0.12 ms.

### 3 Earth orientation, geocenter, and gravity variations

In the previous section on length-of-day variations, only variations in the component of core angular momentum in the direction of the rotation axis have been considered. Variations in this direction are expected since torsional oscillations are considered to dominate the core flow at decadal time scales. However, this does not rule out the possibility that equatorial components of core angular momentum also vary (say at different time scales or through motion linked with the inner core), and that, through angular momentum exchanges between core and mantle, the core can lead to variations in all three components of Earth rotation. Both nutation and polar motion show features that are thought to be linked with the core, and therefore these variations hold the potential to put additional constraints on the core.

The very accurately observed nutations have proven to be very useful to determine values of several parameters of the Earth's interior. By considering electromagnetic coupling between mantle and core as the dissipative mechanism for the observed out-of-phase nutations, Mathews et al. (2002) showed that, to explain the observed nutation amplitudes, especially the annual retrograde nutation, the semi-annual prograde nutation, and the 18.6 retrograde nutation, a high conductance layer of about  $10^8$  S at the base of the mantle is needed. This supports the idea that electromagnetic coupling is the main element in explaining the decadal LOD variations and moreover gives the same order of magnitude for the conductance as the LOD studies. The radial magnetic field is estimated to be 0.69 mT at the CMB and 7.17 mT at the ICB. The value at the CMB slightly exceeds the extrapolated value of the geomagnetic field of 0.44 mT (Langel and Estes 1982). At the ICB, geodynamo simulations give radial magnetic fields of between 2 and 3.5 mT (Kuang and Bloxham 1999).

Polar motion shows decadal variations of several tens of milliarcseconds (present daily estimates of polar motion are accurate to  $\pm 0.1$  mas, McCarthy 2000) that are difficult to explain by atmosphere or surface processes. These variations have first been claimed by Markowitz (1960), and the variations with period of about 30yr are called the Markowitz wobble. Schuh et al. (2000) found several additional decadal periods going from 7yr to 86yr. The effects of oceans are not well known, and several authors have considered torques of the core on the mantle as the main origin of these observed polar motion variations. The main difficulties are that the needed torque is one order of magnitude larger than the torque necessary to explain the decadal LOD variations (which is difficult

to reconcile given the same model for conductance and CMB topography to explain the LOD variations), and that at these time scales the torsional oscillations are dominant and only lead to core angular momentum variations in the polar direction. Greiner-Mai et al. (2000) used an angular momentum approach to study whether motions of the inner core can lead to similar polar motion variations as those observed. In particular, they assumed that the figure axis of the inner core is aligned with the geomagnetic dipole axis and follows the observed decadal variations of that dipole axis. They found that the mass redistributions, caused by the relative rotation of the denser flattened inner core with respect to the less dense outer core, give about the correct polar motion magnitude. However, no reason for this large inner core tilt is known, instead, strong pressure and gravitational forces tend to align the inner core axis with that of the Earth. In a follow-up study, Greiner-Mai and Barthelmes (2001) did not use the hypotheses on the inner core tilt anymore, and determined, from the excitation functions, the variations in the figure axis of the inner core necessary to explain the observed decadal polar motion. The angle between the figure axis of the inner core and the mantle is found by Greiner-Mai and Barthelmes (2001) to vary between  $0.4^\circ$  and  $1.5^\circ$ , and the figure axis rotates eastwards with a mean velocity of  $0.7^\circ \text{ yr}^{-1}$  but showing large variations of several degrees. In a recent paper, Dumberry and Bloxham (2002) addressed the same problem, but from another point of view. These authors showed that an equatorial torque at the inner core boundary of about  $10^{20} \text{ Nm}$  is needed to explain the decadal polar motion, and that this torque tilts the inner core out of alignment with the mantle by  $0.07^\circ$ , the latter value being much smaller than the result of Greiner-Mai and Barthelmes (2001). Such a torque could be obtained by electromagnetic coupling between the inner core and the torsional oscillations in the outer core for a radial magnetic field at the inner core boundary of 3 to 4 mT, corresponding to the geodynamo simulations estimate.

Small variations in the Earth's gravity field can be induced by changing density structures in the core. Degree one variations describe the variations in the geocenter. Gravity field variations caused by the convective motions have recently been calculated from the output of geodynamo models by Kuang and Chao (2002b). They find gravity field variations of the order of  $10^{-10}$  relative to the mean gravity field of the Earth. Their study was motivated by the observation, from satellite laser ranging (SLR), that the Earth's dynamic oblateness  $J_2$  has suddenly, around 1998, changed its decreasing trend, mainly attributed to postglacial rebound, to an almost equally large increasing trend (Cox and Chao 2002). Changes in core flow around that same period are expected from geomagnetic observations, notably the occurrence of a major geomagnetic jerk, or sudden change in the trend of the geomagnetic secular variation, in 1999 (Mandea et al. 2000). The results of the geodynamo models, however, indicate that these core flow changes can, depending on model assumptions, only account for about one tenth of the observed  $J_2$  change. Greiner-Mai and Barthelmes (2001) estimated degree two gravity field variations for their model of relative inner core rotation to be of the order of  $10^{-10}$  to  $10^{-12}$ , with variations of the order of  $10^{-12} \text{ yr}^{-1}$ . These variations could possibly be measured by the GRACE mission and can then give information on core dynamics.

## 4 Present status of the SBC

The SBC has about twenty members from the fields of geomagnetism, Earth rotation, geodynamo modeling (numerical and experimental), and gravimetry. In contrast to other geophysical flows such as the atmosphere and the oceans, the geophysical fluid under study for the SBC, the fluid outer core, can not be observed directly. This constitutes a problem, observational data on the core is limited and the calculation of various core effects is necessarily based

on modelisations, but also an advantage, a lot is to be learnt about the core from studying observational data that is influenced indirectly by the core. The data on core flow are derived mainly from geomagnetism. This information is only indirect because the mantle and crust, between the observer and the core, influence the magnetic observations and partly hide the core field. One of the tasks of the SBC then is to keep contact with, e.g., the geomagnetism and geodynamo community.

The SBC promotes and stimulates research on core dynamics. As a first step in achieving this goal, the SBC has created a website ([www.astro.oma.be/SBC/main.html](http://www.astro.oma.be/SBC/main.html)). Because of the multidisciplinary nature of our activities, we give there a description of the relevant theories and information necessary to understand and use the data. Subjects treated include: core convection, core flow, geomagnetism, CMB torques, inner core differential rotation, Earth's rotation changes due to the core, and core composition. Additionally, we have built a bibliography of articles relevant to the core that presently contains more than a thousand references.

The SBC collects and makes available relevant data for studies of core dynamics. The data we want to provide include (1) the observed magnetic field and its secular variation, (2) CMB topography derived from seismology or from steady-state convection computation, (3) core flows and angular momentum derived from computations constrained by the observed surface magnetic field and its secular variation, (4) angular momentum derived from LOD data, (5) core flows and angular momentum derived from both LOD variations and surface magnetic field data, (6) core flows and angular momentum from geodynamo modeling, (7) data on core-mantle torques, including viscosity, magnetic fields and core topography (8) data on inner core motion and structure.

The data on angular momentum can already be downloaded directly from the SBC website, for the other data, some web links are provided but most data must still be collected. To be able to make full use of the data, they are documented. In particular, the hypotheses used in the computations are described. Further, a special form for scientists wishing to provide data has been prepared and put on the web site.

Nine series of core angular momentum (CAM) data are at present available on the SBC website:

- Jackson's three different CAM series based on torsional oscillations using the hypothesis of fully time-dependent geostrophic flow and the surface magnetic field UFM1 model of Bloxham and Jackson (1992) (for three different smoothings, see Jackson 1997);
- Petrov's three different CAM series based on torsional oscillations using (a) the IGMF surface magnetic field and the geostrophic flow approximation, (b) the surface magnetic field and the quasi-steady flow approximation, and (c) the LOD observation, the surface magnetic field and the geostrophic flow approximation (Petrov and Dehant, EGS 2000 abstract);
- Jault's CAM based on the torsional oscillations using the tangential geostrophic flow and the surface magnetic field (Jault et al. 1988);
- Pais' CAM based on the torsional oscillations using the tangential geostrophic flow and the surface magnetic field UFM1 model of Bloxham and Jackson (1992), see Pais and Hulot (2000);
- Boggs' core angular momentum (CAM) based on the torsional oscillations using the tangential geostrophic flow and the surface magnetic field UFM1 of Bloxham and Jackson (1992), see Hide et al. (2000).

The various model LOD data are given in Fig. 1.

An AGU monograph, entitled “Earth’s Core: dynamics, structure, rotation” has been prepared by V. Dehant, K. Creager, S. Karato, and S. Zatman (editors).

## 5 Future steps and recommendations

After the initial phase of setting up the website and gathering data, we plan to revise and update the website and to add some new features. In particular, main and new references will be added to the science overview parts of the website. This will be flexible as new references can easily be introduced without the need to revise the concise explanatory texts. To make new results and methods easily available, we will add a section with recent news and highlights. To be able to do that, it would of course be very much appreciated if people would keep us informed of new papers relevant to the SBC. To aid scientists who work or intend to work in core-related studies, an extensive bibliography will be maintained on the SBC website, which is presently ordered alphabetically by first author, and it will be studied whether it would be useful and possible to additionally make a division by content (e.g. by topics from the science overview).

Providing reliable data and methods is one of the main tasks of the SBC. In particular, we plan to include all kinds of data that are needed to calculate the effects of the core on LOD variations, nutation, polar motion, surface gravity changes, geocenter variations, and surface deformations. At present, only data on polar core angular momentum in the form of LOD variations at one (or more) year interval are available on the SBC website. More extensive data sets are clearly needed. For LOD studies, data on torsional oscillations must be made available. But also data on other components of the core flow, and of core angular momentum in all directions is needed. To better understand the core-mantle coupling, data relevant to the different coupling mechanisms are important, such as data on top core flow with high resolution, data on the CMB topography, data on the lower mantle conductance, and data on magnetic field strengths. In this sense, data from geodynamo modeling seem very interesting. In addition, we plan to add data on the inner core (relative motion, magnetic field strength, ICB topography,...). It is recommended that the members of the SBC make these data available, and actively stimulate others to do so. We plan to test and validate the data by intercomparison and hypothesis testing to be able to provide reliable data sets.

One of the goals of the SBC is to make the geophysical community aware of the various geodetic effects that could be linked with the core and to stimulate research in this field. It is important to bring together different groups with expertise in different aspects of the relevant topics, so that, by sharing expertise and working together, the whole group can achieve more than the sum of their individual contributions. At the joint EGS-AGU-EUG meeting in Nice in April 2003, a session will be organized on “Earth Rotation and Polar Wander: Internal Processes”, and we also foresee a business meeting at that occasion with the SBC members to discuss future activities. The adaptation of our website as described above is foreseen for that period. The following items could be discussed: which data should be made available, which formats should be used, would it be interesting or needed to distribute software, what is the usefulness of the present services, which new activities need to be undertaken,...

Our work and our web site can only be up-to-date if sufficient interactions exist with the scientific community related to the Earth’s rotation and to the Earth’s core. Any constructive comment or information is welcome. Our web-master, Lydia Van Camp, will receive them with great pleasure ([lydia.vancamp@oma.be](mailto:lydia.vancamp@oma.be)). You may of course also contact one of the SBC team members.

Current and future projects look very promising. Satellite mission like Oersted and CHAMP provide high-quality vector magnetic field data. We thus obtain a better resolution of the magnetic field, which will in turn lead to improved models of core flow. It is also likely that the secular variation can be obtained at spherical harmonic degrees higher than 13. The lithospheric field dominates at these high degrees, but as this field is believed to vary very slowly in time, the time variations of the high degree geomagnetic field can be used to probe the Earth's core. Several missions, such as CHAMP, GRACE and GOCE, will also (and already do) improve the resolution and precision of the gravity field to an extent that core processes can be detected. In the coming years, we can therefore expect significant new insight in core dynamics and an improved understanding of variations in Earth orientation and gravity field.

## References

- [30] Bloxham, J., and Jackson, A., Time-dependent mapping of the magnetic field at the core-mantle boundary, *J. Geophys. Res.*, **97**, 19537-19563, 1992.
- [30] Braginsky, S.I., 1970, Torsional magnetohydrodynamic vibrations in the Earth's core and variations in length of day, *Geomag. Aeron. Engl. Transl.* 10, 1-8
- [30] Buffett, B.A., 1996, A mechanism for decade fluctuations in the length of day, *Geophys. Res. Lett.* 23, 3803-3806
- [30] Buffett, B.A., 1999, A comparison of geodetic and seismic estimates of inner-core rotation, *Geophys. Res. Lett.* 26, 1509-1512
- [30] Buffett, B.A. Garnero, E.J., Jeanloz, R., 2000, Sediments at the top of the Earth's Core, *Science* 290, 1338-1342
- [30] Cox, C.M., Chao, B.F., 2002, Detection of a Large-Scale Mass Redistribution in the Terrestrial System Since 1998, *Science* 297, 831-833
- [30] Dumberry, M, Bloxham, J., 2002, Inner core tilt and polar motion, *Geophysical Journal International* 151, 377
- [30] Garcia, R., Souriau, A., 2000, Amplitude of the core-mantle boundary topography estimated by stochastic analysis of core phases, *PEPI* 117, 345-359
- [30] Greiner-Mai, H., Jochmann H., Barthelmes, F., 2000, Influence of inner-core motions on the polar motion and the gravity field, *PEPI* 117, 81-93
- [30] Greiner-Mai, H, Barthelmes, F., 2001, Relative wobble of the Earth's inner core derived from polar motion and associated gravity variations, *Geophysical Journal International* 144, 27-36
- [30] Hide, R., Boggs, D.H., and Dickey, J.O., 2000, Angular momentum fluctuations within the Earth's liquid core and torsional oscillations of the core-mantle system, *Geophys. J. Int.* 143, 777-786
- [30] Holme, R., 1998, Electromagnetic core-mantle coupling –I. Explaining decadal changes in the length of day, *Geophys. J. Int.* 132 167-180
- [30] Holme, R., 2002, Probing the core with observational geomagnetism, *SEDI 2002 abstract book*, 38-39
- [30] Jackson, A., 1997, Time-dependency of tangentially geostrophic core surface motions, *PEPI* 103, 293-311

- [30] Jault D., Gire C., and Le Mouél J.-L., 1988, Westward drift, core motions and exchanges of angular momentum between core and mantle, *Nature*, 333, 353-356
- [30] Jault D., Le Mouél J.-L., 1989, The topographic torque associated with a tangentially geostrophic motion at the core surface and inferences on the flow inside the core, *Geophys. Astrophys. Fluid Dynamics* 48, 273-296
- [30] Langel, R.A., Estes, R.H., 1982, A geomagnetic field spectrum, *Geophys. Res. Lett.* 9, 250-253
- [30] Kuang, W.J., Bloxham, J., 1999, Numerical modelling of magnetohydrodynamic convection in a rapidly rotating spherical shell: Weak and strong field dynamo action, *J. Comput. Phys.* 153, 51-81
- [30] Kuang, W., Chao, B.F., 2001, Topographic Core-Mantle coupling in Geodynamo modeling, *Geophys. Res. Lett.* 28, 1871-1874
- [30] Kuang, W., Chao, B.F., 2002a, Geodynamo Modeling and Core-Mantle Interactions, in: *Earth's Core: Dynamics, structure, rotation*, eds. V. Dehant, K. Creager, S. Karato, S. Zatman, AGU monograph, 2002,
- [30] Kuang, W., Chao, B.F., 2002b, On the effect of Mass Redistribution in the Core on Time-Varying Gravity at the Earth's Surface, *SEDI 2002 Abstract book*, 57
- [30] Laske, G., Masters, G., 2002, The Earth's Free Oscillations and the Differential Rotation of the Inner Core, *SEDI 2002 Abstract book*, 37
- [30] Manda, M., Bellanger, E., Le Mouél, J.-L., 2000, *Earth Planet. Sci. Lett.* 183, 369
- [30] Markowitz, W.M., 1960, in: *Methods and Techniques in Geophysics*, Vol. I, S.K. Runcorn (ed.), Interscience, New York, 325
- [30] Mathews, P.M., Herring, T.A. and Buffett, B.A., 2002, Modeling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earth's interior, *J. Geophys. Res.* vol. 107 (B4), 10.1029/2001JB00039
- [30] Mound, J.E., Buffett, B.A., 2002, Rotational Free Oscillations of the Core and Mantle, preprint; see also, Free Oscillations in the Axial Rotation of the Core-Mantle System, *SEDI 2002 Abstract book*, 32
- [30] Pais, A., Hulot, G., 2000, Length of day decade variations, torsional oscillations and inner core superrotation: evidence from recovered core surface zonal flows, *PEPI* 118, 291-316
- [30] Ponsar, S., Dehant, V., Holme, R., Jault, D., Pais, A., Van Hoolst, T., The Core and fluctuations in the Earth's rotation, in: *Earth's Core: Dynamics, structure, rotation*, eds. V. Dehant, K. Creager, S. Karato, S. Zatman, AGU monograph, 2002,
- [30] Schuh, H., Richter, B., Nagel, S., 2000, Analysis of Long Time Series of Polar Motion, in: *Polar Motion: Historical and Scientific Problems*, Proceedings of IAU Colloquium 178, Astronomical Society of the Pacific Conference Series Vol. 208, S. Dick, D. McCarthy, B. Luzum (eds.), San Francisco, p. 321-331
- [30] Sze, E.K.M., van der Hilst, R.D., 2002, Core Mantle Boundary Topography from Short Period PcP, PKP, and PKKP Data. *PEPI*, in press