“Understanding the Earth core and nutation.” Abstract Book

Brussels, September 2016

Contents

Monday Talks

Drilling the Earth down to the core with VLBI.

19 Sep
14:10

Sebastien Lambert, Cesar Gattano
SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE

Born in the second part of the XXth century with the aims of resolving milliarc-second structure of newly discovered quasars and measuring crustal motions at the centimeter level, very long baseline radio interferometry remains the only technique able to measure the Earth's rotation axis orientation with respect to space (that is Universal Time UT1 and the nutation angles). The presence of a liquid core and a, presumably solid, inner core inside the Earth's mantle produce three resonances, amplifying thus the amplitude of the nutations, and allowing astronomers and geophysicists to infer some core and inner core parameters by comparing the VLBI-observed nutation with nutations of a simplified (e.g., rigid) Earth.

Another interesting signature of the liquid core in nutation is the so-called free core nutation (FCN), a forced-free motion of the mantle that reflects a free rotational mode of the liquid in the core. This motion is clearly visible in modern VLBI analysis results. Its variable amplitude and phase currently brings more questions than answers concerning the possible excitation mechanisms.

In this talk, I will address the VLBI technique and its accuracy, as well as the recent attempts to determine and improve some of the Earth's interior parameters on the basis of VLBI observations, including observation of the FCN.

Evolution of the VLBI EOP precision and accuracy over the past 37 years.

19 Sep
14:40

Zinovy Malkin
Pulkovo Observatory

More than 13 million observations (VLBI delays) obtained during the 37 years of geodetic and astrometric VLBI programs are stored in the International VLBI Service for Geodesy and Astrometry (IVS) data centers and publicly available for scientific analysis. This presentation is devoted to analysis of various statistics related to the VLBI observations, EOP determinations, and other. Despite historical interest, this statistics can be useful to solve practical tasks, such as, e.g., selection of an optimal data interval for various studies or investigation of EOP accuracy and precision on the network geometry and other factors.

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19 Sep
15:00

SOFA & lAU Standards.

Catherine Hohenkerk

HM Nautical Almanac Office, UK Hydrographic Office

This talk summarises the role of the International Astronomical Union's (IAU) Standards of Fundamental Astronomy's (SOFA) Board and its software libraries over some 20 years. The new IAU Commission A3—Fundamental Standards—will also be promoted, which illustrates the benefit of well-defined standards, and the importance of standards in many applications including those that use Earth rotation parameters.

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19 Sep
15:50

30 years in the concept and use of the non-rotating origin.

Nicole Capitaine

SYRTE, Observatoire de Paris, France

The concept of non-rotating origin (NRO) was first proposed by B. Guinot in 1979. Then, a theory of the NRO (Capitaine et al.,1986) was developed, which provided a semi-analytical development for locating the NRO with a precision of 10 μas and showed that the uncertainties on the precession-nutation model had negligible consequences. Such computations used the direction cosines, X, Y (or coordinates of the pole in the Geocentric celestial reference system, GCRS). A subsequent study of those coordinates showed that they could advantageously replace the usual precession and nutation quantities and provided their semi-analytical development consistent with the IAU precession-nutation model in force at that time. Then, progressively, the acceptance of the NRO, and more generally of the new paradigm (the NRO and the GCRS coordinates) for the coordinate transformation between the ITRS (International terrestrial reference system) and the GCRS progressed. That option was considered in the IERS Conventions 1996 and was adopted by IAU 2000 Resolution B1.8. That Resolution recommended using the "non-rotating origins" as origins on the equator of the Celestial intermediate pole in the GCRS and ITRS; they were re-named "Celestial and Terrestrial intermediate origins" (CIO and TIO), respectively by IAU 2006 Resolution B2. Their kinematical property provides a very straightforward definition of the Earth's diurnal rotation based on the Earth Rotation Angle (ERA) between those two origins. The definition of UT1 was redefined as being linearly proportional to the ERA through a conventional formula. Of paramount importance have been the comparison tests with the use of the equinox, made between 2000 and 2003 in cooperation between Paris Observatory, the HM Nautical Almanac Office, UK and the US Naval Observatory, as part of the preparation of the IERS Conventions 2003 and software for their implementation. They were extended in coordination with the group SOFA (Standards Of Fundamental Astronomy) of the IAU (Wallace 2002). This showed that the use of the NRO was simpler and less exposed to the risk of error that the use of the equinox and was the basis for the practical implementation of the IAU resolutions in The Astronomical Almanac in 2006. Since then, applications of the new paradigm

have continued to expand, in reference books in astrometry, in the high-precision astrometric observations processing software, astronomical ephemeris and almanacs. The comparisons at the micro-arcsecond from developments consistent with the IAU 2006/2000 precession-nutation, the recommendations of the IERS Conventions 2010 and the 2007 version of the SOFA software, encouraged broad adoption of the new paradigm. All these studies have largely beneficed from the international discussions that took place during the Journées, the IAU meetings and within working groups.

Thirty years in the theory of nutation – A tribute to Journées "Systèmes de référence spatio-temporels".

19 Sep
16:20

Chengli Huang[1], Alberto Escapa[2], and Jean Souchay[3]

[1]Shanghai Astronomical Observatory, Chinese Academy of Sciences, China; [2]Dept. Aerospace Engineering, University of León, Spain; [3]SYRTE, Observatoire de Paris, France

The theories of nutation and precession of the Earth have played an important role in the development of Journées "Systèmes de référence spatio-temporels" (JSR) during its more than twenty editions. It has become the natural forum for discussion of the enhancements of those theories in a period of intense activities in this field.

That intensity has been a consequence of the progressive substitution of International Astronomical Union (IAU) standards with higher accuracy models. In fact, different working groups on Earth rotation like, for example, IAU/IUGG Working Group on Non-rigid Earth nutation theory (1994-2000), IAU Working Group on Precession and the Ecliptic (2003-2006), or IAU/IAG Joint Working Group on Theory of Earth Rotation (2013-2015) held many discussions in JSR, being the seeds to adopt new IAU Resolutions.

We present a perspective of the evolution of these theories in the last thirty years. More than providing a comprehensive exposition of all the related investigations of this field, we have preferred to make some representative choice based on our personal trajectory together with the Journées.

In particular, there are distinguished three different but interrelated topics. The first one considers the theory of rigid Earth nutation, a necessary proxy for some more advanced models, and the precession of the Earth. The second makes a review of the Hamiltonian theory of the non-rigid Earth that has been present in JSR almost in all its editions since 1995. Finally, the non-rigid Earth nutation models are considered but from a geophysical point of view, closer to actual IAU2000 nutation model, highlighting some of their contributions to a better understanding of the interior properties of our planet.

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19 Sep 16:50

The "Journées" - A unique international forum for discussion on space and time reference systems.

Yaroslav Yatskiv[1], Nicole Capitaine[2]

[1]Main Astronomical Observatory of the NAS of Ukraine; [2]Paris Observatory, SYRTE, France

A brief survey of the organization, history, goals and achievements of "The Journées Systèmes de référence spatio-temporels" is presented, since their beginning, in 1988, as being French scientific meetings, until the following 25 years during when they have gradually become international multidisciplinary forum of scientific and practical importance for experts in the fields of astrometry, celestial mechanics, geodesy and geophysics. Their role in the preparation of the IAU 2000-2009 Resolutions, the development of scientific cooperations between various institutes in the world, as well as their coordination with other international series of conferences, such as the Orlov conferences and the Lohrmann-Kolloquium, is discussed.

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19 Sep 17:20

Nicole Capitaine, a dedicated career.

Veronique Dehant

Royal Observatory of Belgium

Nicole Capitaine is honoured today because of her dedicated career to Earth rotation, in particular in the frame of the Journées Systèmes de Référence spatio-temporels. She participated in the national and international organization of Fundamental astronomy and Space Geodesy and dedicated her-self to their development and their international scientific services. She was assigned with many responsibilities in international scientific bodies and participated in various national and international committees. Nicole Capitaine conducted scientific researches within a broad international cooperation, aiming at a better definition and realization of reference systems and time scales for astronomy and space dynamics and a better understanding of Earth's rotation. Her contribution to scientific works led to the adoption, through international resolutions by the IAU and the IUGG, of new concepts, definitions, parameters and models for astronomy and geodesy, which are essential for many applications to space dynamics and dynamics of solar system bodies.

Tuesday Talks

The Free Rotational Modes of the Earth: A Review.

20 Sep
09:00

Richard Gross

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

The Earth is a dynamic system—it has a fluid, mobile atmosphere and oceans, a continually changing global distribution of ice, snow, and water, a fluid core that is undergoing some type of hydromagnetic motion, a mantle both thermally convecting and rebounding from the glacial loading of the last ice age, and mobile tectonic plates. In addition, external forces due to the gravitational attraction of the Sun, Moon, and planets also act upon the Earth. These internal dynamical processes and external gravitational forces exert torques on the solid Earth, or displace its mass, thereby causing the Earth's rotation to change, with the frequency of the change being the same as the frequency of the driving torque. In addition, the Earth's rotation possesses a number of free rotational modes whose frequencies are not associated with any driving torque but are instead a function of the structural and rheological properties of the Earth. The 14-month Chandler wobble is a free rotational mode that exists because the Earth is not spherically symmetric. The Free Core Nutation, also known as the Nearly Diurnal Free Wobble or the Retrograde Free Core Nutation, is a free rotational mode that exists because the Earth has a fluid outer core that is not spherically symmetric. And both the Free Inner Core Nutation, also known as the Prograde Free Core Nutation, and the Inner Core Wobble are free rotational modes that exist because the Earth has a solid inner core that is not spherically symmetric. Because the frequencies of these four free rotational modes of the Earth are a function of the internal structure and rheology of the Earth, observations of their frequencies can be used to gain greater understanding of the Earth's deep interior. In this presentation, the observations and analysis of the free rotational modes of the Earth will be reviewed.

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20 Sep
09:30

New method of computing parameters of Free Core Nutation.

Jan Vondrák, Cyril Ron

Astronomical Institute, Czech Academy of Sciences, Prague

Traditionally, the period T and quality factor Q of the Free Core Nutation (FCN) are derived from VLBI-based celestial pole offsets (CPO). To this end, either the direct analysis of the observed values of CPO, or indirect method consisting in studying resonant effects of nutation terms with frequencies close to FCN, are used. The latter method is usually preferred, since it yields more accurate results. Here we propose a new method, based on combination of both. We integrate numerically the part of CPO that is due to geophysical excitations for different combinations of T, Q, using Brzeziński's broad-band Liouville equations, and compare the results with the observed values of CPO. The values yielding the best fit are then estimated. The observed CPO, however, must be first corrected for the change of nutation that is caused by the T, Q values different from those used to calculate IAU 2000 model of nutation. To this end, we are using Mathews-Herring-Buffet transfer function and apply it to the five most influenced terms of nutation (with periods 365.26, 182.62, 121.75, 27.55 and 13.66 days). The results, obtained from the data in the interval 1986.0—2016.0, will be presented in two variants: with only atmospheric/oceanic excitations, and with impulse-like excitations due to geomagnetic jerks added.

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20 Sep
09:50

How much FCN model depends on the underlying CPO series?

Zinovy Malkin

Pulkovo Observatory

The dependence of the FCN model on the underlying CPO series was investigated. For this purpose, several FCN series were computed using the same strategy analogous to that used for the IERS FCN model (Lambert, 2007, 2016) but from different CPO series. The model coefficients Ac, As, Xo, and Yo were computed for a sequence of sliding windows with different width and shift of one day. Then the differences among the FCN series, as well as the differences among their amplitude and phase variations were investigated. Preliminary result showed that the RMS differences among the FCN models derived from different CPO series are considerably smaller than the differences among the CPO series, which can be primarily explained by smoothing effect. Systematic differences among the CPO series propagates to FCN model, which mostly affects the bias terms Xo and Yo. The analysis of the differences between the IVS and IERS combined CPO series showed that the IVS series looks to be preferable for both precession-nutation and FCN-related studies.

Recent advances in modeling and observation of polar motion at daily and subdaily periods: an overview

20 Sep
10:30

Aleksander Brzezinski[1,2]

[1]Warsaw University of Technology, Department of Geodesy and Cartography, [2]Space Research Centre of the Polish Academy of Sciences, Warsaw

Polar motion and universal time UT1 contain physical signals within the diurnal and subdiurnal frequency bands. The dominant part with peak-to-peak amplitude approaching the level of 1 milliarcsecond (mas) is due to the gravitationally forced ocean tides. There is also a small variation (¡0.1 mas) designated as libration, caused by direct influence of the tidal gravitation on the triaxial structure of the Earth. The remaining part (¡0.1 mas) comprises the atmospheric and nontidal oceanic influences driven by the daily cycle in the solar heating. Despite the small size, the diurnal and subdiurnal signals in Earth rotation are important for understanding the high frequency global dynamics of the solid Earth and the overlying fluid layers.

Such high frequency variations in Earth rotation could not be observed by the methods of optical astrometry because the observations were not sufficiently accurate and their sampling interval was significantly longer than 1 day. Hence all earlier predictions were purely theoretical based on the knowledge about the shape and internal constitution of the Earth. Practically all observational evidence of diurnal and subdiurnal variations in Earth rotation has been gathered during the last three decades. The high resolution observations of Earth orientation are still under development. An important and independent method of modeling diurnal/subdiurnal variations in Earth orientation is by the high resolution estimation of the total angular momentum of geophysical fluids, primarily the atmosphere and the oceans.

This paper gives an overview of the recent advances in theoretical modeling and observation of polar motion at daily and subdaily periods. Our particular interest is in the possibility of monitoring high frequency geophysical signals which are irregular to some extent therefore unpredictable and cannot be described by simple analytical models.

Polar Motion Excitation From CMIP5 Climate Models And Earth's Gravity Field Variations.

20 Sep
11:00

Jolanta Nastula[1], Malgorzata Wińsks[2]

[1]Space Research Centre, Polish Academy of Sciences, Poland; [2]Warsaw University of Technology, Poland

Influence of land hydrology on polar motion excitation .can be estimated either from global climate models of the land-based hydrosphere or from the Earth's gravity field variations. In this study a relationship between geodetic residuals being the difference between the geodetic excitation function and sum of the atmospheric and oceanic excitation and hydrological excitation (HAM) is investigated The geodetic residuals describes approximately hydrological signals in polar motion excitation determined from geodetic observations. The hydrological excitation functions are assumed to represent the excitation due to the mass variations over land only. This

study focuses on the impact of the land hydrosphere on polar motion excitation at the long term, seasonal and other seasonal time scales. We estimate hydrological polar motion excitation functions (HAM) from CMIP5 climate models and from Gravity and Climate Recovery Experiment (GRACE) gravity fields. Our analysis showed that none of the analyzed hydrological - gravimetric functions is fully compatible with the geodetic residuals. However there is a good agreement between GRACE based excitation functions and the geodetic residuals at the seasonal time scales.

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20 Sep
11:20

Coupling Constant at CMB and ICB as estimated from VLBI observations.

Ping Zhu, Attilio Rivoldini, Antony Trinh, Raphael Laguerre, Jeremy Rekier, Andres Santiago, Tim Van Hoolst, Veronique Dehant

Royal Observatory of Belgium

Due to the gravitational attractions from celestial bodies, the Earth's rotation axis has various periodical motions w.r.t its figure axis. These motions are named as nutations. The forced nutations can be expressed as a sum of harmonic components and most of them could be precisely modelized and predicted using the orbital information of celestial bodies (Fabin and Dehant 1998, Suscha and Folgueira 2000). Earth's nuations can be directly measured from the very long base line interferometry (VLBI) observations, which were initiated around 60th. VLBI is a technique in which radio telescopes hundreds to thousands of kilometers apart observe the same radio source (Qusars) in the sky. After the digitized signals are combined at a central dedicated data processor (the correlator), the time delays between two antennas, are extracted and corrected from local environmental effects. By combining the individual VLBI observation around the world using Kalman filter, the global VLBI solutions are found. Among them, the Earth's nutations is expressed as the celestial poles offsets (dx, dy). However due to the fact that the real Earth's behaviour is deviated from an elliptical, oceanless, elastic Earth with a fluid outer core and solid inner core earth model (Wahr 1981a,b,c). Therefore, the residuals are remaining large if one compares the observations with the predictions based on this model. On the other hand, The Nutations measured in celestial pole offsets (dx, dy) had been analyzed in detail by (Herring 2002). After fitting those results to a sets of equations, explicitly allows for mantle anelasticity, inner core dynamics, and non-hydrostatic equilibrium effects, Mathew et. al. has obtained several Basic Earth's Parameters (BEP) using the least squares method, this nutation model is referred as MHB2000 (Mathiew et.al 2002). We applied the same approach to the up-to-date VLBI observations. It yields an updated sets of BEPs, which are compared to those values obtained from Bayesian inversion (Koot et.al 2008). Among them the coupling constant at CMB and ICB will openly discussed further.

References: Roosbeek, F., and V. Dehant, RDAN97: An analytical development of rigid Earth nutation series using torque approach, Celestial Mech., 70, 215– 253, 1998.

Souchay, J., and M. Folgueira, The effect of zonal tides on the dynamical ellipticity of the Earth and its influence on the nutation, Earth Moon Planets, 81, 201–216, 2000.

Herring, T. A., P. M. Mathews, and B. A. Buffett, Modeling of nutation and precession: Very long baseline interferometry results, J. Geophys. Res., 10.1029/2001JB000165, in Press, 2002.

Wahr, J. M., A normal mode expansion for the forced response of a rotating Earth, Geophys. J. R. Astron. Soc., 64, 651–675, 1981a.

Wahr, J. M., Body tides on an elliptical, rotating, elastic, and oceanless Earth, Geophys. J. R. Astron. Soc., 64, 677–703, 1981b.

Wahr, J. M., The forced nutations of an elliptical, rotating, elastic, and oceanless Earth, Geophys. J. R. Astron. Soc., 64, 705– 727, 1981c.

Mathews, P.M., Herring, T.A. & 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., 107, 2068, doi: 10.1029/2001JB000390.

Koot, L., Rivoldini, A., de Viron, O. & Dehant, V., 2008. Estimation of Earth interior parameters from a Bayesian inversion of very long baseline interferometry nutation time series , J. geophys. Res., 113, 8414, doi:10.1029/2007JB005409.

Forced Nutations and the Strength of Earth's Internal Magnetic Field.

20 Sep
14:00

Bruce Buffett

University of California, Berkeley

Observations of Earth's forced nutation offer surprising insights into the structure and dynamics of the core. This unique sensitivity is enabled by resonances in the tidal response. Forcing at frequencies close to the resonances drive angular deviations in the rotation of the fluid and solid core, which cause observable changes in the rotation of the surface. Here we focus on phase lags in the tidal response, particularly at frequencies close to the free core nutation (FCN) and the free inner-core nutation (FICN). These phase lags represent the effects of dissipative processes associated with differential rotations of the fluid and solid cores.

The frequency of the retrograde annual nutation is close enough to the frequency of the FCN that the associated phase lag is widely attributed to dissipative coupling at the core-mantle boundary. Magnetic coupling is a viable interpretation, but it requires a radial magnetic field of roughly 0.6 mT and a thin conducting layer on the mantle-side of the boundary. Numerical dynamo models support the required estimate for the radial magnetic field, but the origin of a conducting layer is more controversial. A plausible explanation depends on the presence of stable stratification at the top of the core. The combination of stable stratification and boundary topography trap fluid near the boundary, causing it to move with the mantle. Electric currents in the trapped regions are sufficient to explain the observations.

An additional source of dissipation is observed through the phase lag of the retrograde 18.6-year nutation. This frequency is close enough to the frequency of the FICN that the associated resonance contributes to the forced response. Rotation of the inner core relative to the fluid outer core generates inertial waves, which are organized into narrow shear layers. Distortion of the magnetic field throughout the outer core damps the motion through Ohmic dissipation. The observed dissipation can be explained with a volume-averaged magnetic field strength of 2.5 mT in the bulk outer core. Thus, nutation observations provide two unique constraints on the strength of the magnetic field deep inside the planet.

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20 Sep
14:30

Probing Earth's Core Structure with Geomagnetic and Length-of-Day Variation.

Nicholas Knezek, Bruce Buffett

Department of Earth and Planetary Science, U.C. Berkeley

Earth's liquid core hosts a diverse set of waves with periods ranging from days to thousands of years. The fluid motions associated with these waves are thought to be important both for interpreting historical fluctuations in the geomagnetic field and changes in Earth's length-of-day. Geomagnetic secular variation and LOD-variations provide us with two independent sources of data to study the core's internal structure and state and the strength of the core's interaction with the rest of the planet.

One class of waves with periods of several decades is known to arise from an interplay between magnetic, Archimedes buoyancy, and Coriolis forces. A collection of these so-called MAC waves provide a good description of time-dependent zonal flow at the top of the core and produce a 60-year fluctuation in the strength of Earth's dipole field similar to observations. This set of waves requires a buoyant layer of core fluid stable to convection near the core-mantle boundary with a thickness of 140 km and a buoyancy frequency comparable to Earth's rotation rate. Through electromagnetic coupling to the inner core and inner core gravitational coupling to the mantle, these waves can also produce the observed decadal variations in Earth's length of day. These results offer support for stable stratification at the top of the core and suggest a common origin for decadal fluctuations in the geomagnetic field and the LOD.

The proposed 140 km thick stably-stratified layer near the core-mantle boundary should also support a wide variety of waves similar to those that arise in Earth's oceans or atmospheres. These magnetohydrodynamic waves are too complex to study using simple analytical methods, so we are developing a new numerical model to examine their influence on historical measurements of Earth's geomagnetic field. We apply the model to investigate equatorially-trapped magnetic Rossby waves, which have been proposed as an explanation for drifting flux patches near Earth's equator. We assess the viability of this interpretation and explore other possible explanations.

Earth's angular momentum variation from numerical geodynamo simulation: towards assimilation of the observed EOP variation.

20 Sep
15:00

Weijia Kuang

Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center

It has long been speculated that the observed EOP variation on decadal time scales could be due to exchanges of angular momentum between the solid mantle and the (dynamic) liquid outer core. Past results (Jault et al. 1988; Holme and Whaler 2001; Gillet et al. 2010) have confirmed that the core-mantle angular momentum exchange is responsible for the length-of-day (LOD), i.e. the rotation rate, variations on time scales of several years to several decades. Consequently, the observed EOP variation can provide additional (and independent) constraints on the core fluid flow, and should therefore be assimilated with numerical geodynamo models, thus improving our understandings of core fluid motion and core-mantle interactions, and our interpretations of the observations.

To make this to work, however, we must first investigate the 3-dimensional rotation of the solid mantle obtained from numerical models that are operated with the parameter values far from those appropriate for the Earth's core, such as those of the Rossby number which directly control the core fluid inertia, thus its angular momentum variation. In this presentation, I will show, using our own geodynamo model (Kuang and Bloxham, 1997; Kuang and Chao 2003; Jiang and Kuang 2008) solutions, that current geodynamo models with the Rossby number smaller than 10-6 should be sufficient to obtain angular velocity variations on decadal and longer time scales. Furthermore, the amplitudes of such variations are comparable to those from the surface geodetic observations, implying that core-mantle interactions should be a prominent mechanism in explaining decadal EOP variations. It also suggests that the observed EOP variation can now be assimilated with numerical geodynamo models to better estimate the core flow.

Body tides and surface loading of a rotating and laterally heterogeneous Earth model.

20 Sep
15:50

Jun-Yi Guo

School of Earth Sciences, The Ohio-State University

We present a theory on the deformation of a rotating and laterally heterogeneous Earth model for body tides and surface loading by generalizing the Love numbers of a non-rotating spherically symmetrical elastic Earth model. The influences from rotation and lateral heterogeneity are formulated based on a perturbation method. As a result, the perturbation part of the Love numbers of any degree and order forcing spreads to the whole spectrum of spherical harmonic expansion, and toroidal deformation terms appear. We propose to solve the ordinary differential equations using the Chebyshev-Collocation method, which not only transforms differential equations to algebraic equations quite straightforwardly, but also allows straightforward computation of higher order derivatives of the solution, permitting easy inclusion of

higher order perturbations. Products between the perturbation variables and the solution of the non-rotating spherical Earth model are computed according to the concept of pseudospectral method: We first transform the spherical harmonic series to space domain, compute the products in space domain, and then transform back to spherical harmonic series. This avoids the somewhat tedious product to sum formula of spherical harmonics.

An accompanying problem is the computation of initial gravitational field and stress arisen from lateral heterogeneity. While the initial gravitational field can be computed uniquely from density, the initial stress is not uniquely determined. In deriving the equation of infinitesimal deformation of the Earth, the initial stress is assumed to balance the gravity (the Earth can no longer be assumed in hydrostatic equilibrium in the presence of lateral heterogeneity), providing a gravity-stress relation, which the initial stress should satisfy. However, this relation does not uniquely determine the stress, and further assumptions should be made for the stress to be unique. Fortunately, a general solution of stress from the gravity-stress relation has been provided in the literature. Here we seek the solution that deviates least from hydrostatic equilibrium by minimizing the deviatoric part in a global sense. The mathematical problem is then the minimization of a functional, which we transform to an algebraic problem based on the Chebyshev-Collocation method.

Although here the perturbation-pseudospectral approach is applied to compute influence of heterogeneity on Love numbers, it could also be used to compute the influence of heterogeneity, including topography of core-mantle boundary, on rotational modes of the Earth, which are crucial in the computation of transfer functions for nutations of a non-rigid Earth.

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20 Sep
16:20

Nutations and librations of non-hydrostatic planets and moons

Antony Trinh

Royal Observatory of Belgium

We discuss our efforts towards an extension of John Wahr's biaxial, hydrostatic nutation model to a more general Earth. Using a similar, triaxial, non-hydrostatic libration model, we also show that Cassini's libration observations constrain the thickness of Enceladus's ice shell. We use TenGSHui, a Mathematica package for tensor equations in slightly aspherical domains, to automate our calculations.

A mechanism that would make the frequency of a rotational mode double or multiple.

20 Sep 16:40

Yves Rogister[1], Bernard Valette[2]

[1]Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, France; [2]Institut des Sciences de la Terre, Chambéry, France

Ten years after Chandler discovered a free wobble in polar motion data, interpreted as the Eulerian precession, he suggested that it might actually be double. In the 20th century, a series of papers reporting on the analysis of polar motion data reached the same conclusion. In addition to being disputable from a data analysis perspective, the multiplicity of the Chandler wobble lacked for a physical explanation. We try and provide a mechanism responsible for a double Chandler wobble by invoking the dynamics of the liquid outer core. Depending on the core stratification quantified by the squared Brunt-Vaïsälä frequency N^2, the interaction between the inertia-gravity modes of the liquid core and the Chandler wobble can indeed give rise to an avoided crossing phenomenon, which results in two modes sharing similar displacements, that is, an almost rigid wobble of the mantle and oscillations in the outer core having roughly the same amplitude. We also investigate the interactions between modes of the liquid core and the free inner core nutation. By considering a very simple Earth model, we show that the dynamics of a neutrally stratified outer core may generate a family of inner core wobbles with periods ranging from a few dozens to thousands of days.

Coupling planetary rotation to internal fluid layer dynamics

20 Sep 17:10

Jeremy Rekier, Santiago A. Triana, Antony Trinh, Raphaël Laguerre, Ping Zhu, Véronique Dehant

Royal Observatory of Belgium

This work, aims to improve our current understanding of the coupled dynamics of a fluid layer and planetary rotation. We present a method to solve for the eigenmodes of the coupled system based on the new model involving the joined solution of the linearised Navier-Stokes equation and the Liouville equation. The code that we have developed for this purpose relies on a spherical harmonics decomposition in the angular directions and a recently proposed polynomial decomposition in the radial direction producing very sparse, and consequently readily invertible, matrices so that one can hope to reach very demanding ranges of parameters in a reasonable amount of computational time. We discuss the details of the method for coupling to the Liouville equation and present some of the promising preliminary successes of our code. These include the very good agreement with the expected solutions both in the inviscid and viscous cases in a full sphere and a spherical shell. We also present our first results in the process of extending the method to the oblate spheroidal case both for the coupled and the uncoupled systems.

Wednesday Talks

21 Sep
09:00

Precession, magnetic induction, and acoustic modal velocimetry in the laboratory.

Daniel Lathrop

IREAP and IPST, University of Maryland

We present results from the three-meter liquid sodium spherical Couette experiment. We study precession, hydrodynamic and hydromagnetic phenomena in rapidly rotating turbulence as well as magnetic field induction by those flows, in a device geometrically similar to the Earth's outer core. Two external electromagnets apply dipole or quadrupole magnetic fields, while an array of 31 external Hall sensors measure the resulting induced magnetic fields. This allows us to study dynamo gain (as we yet have no self-generating magnetic dynamo) and a broader range of rotating turbulence phenomena. We report substantial magnetic field gain for a variety of flow states. One of these states exhibits bistability in the hydrodynamic flow, with average magnetic field gain of 15

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21 Sep
09:30

Inertial modes in a differentially rotating spherical shell.

Santiago Triana[1], Ankit Barit[2], Raphael Laguerre[1], Johannes Wicht[2]

[1]Royal Observatory of Belgium; [2]Max Planck Institute for Solar System Research

The Earth is a relatively fast rotator and as such it supports Coriolis-restored oscillations in its fluid outer core. These waves can lead to global oscillations, so called inertial modes, that can be excited through precession, libration, or differential rotation of the inner core. The first two mechanisms are fairly well understood as they usually involve inertial modes whose frequencies match the frequency of the forcing. Relatively recent experiments (Maryland, Cottbus) have shown that differential rotation of an inner core can lead to efficient inertial wave excitation. The forcing in this case seems to induce inertial waves via instabilities in the so-called Stewartson layer, a shear layer in the tangent cylinder around the inner core. To elucidate the nature of these inertial wave instabilities, we have performed numerical simulations that match the experimental results. The Cottbus experiments and the simulations have revealed a much richer picture than previously thought. We present an overview of the phenomena as the amount of differential rotation is varied. We discuss briefly the relevance of inertial waves and their angular momentum transport properties in the context of the Earth's core and beyond.

Tides and libration driven elliptical instabilities in planetary cores: non-linear saturation and dynamo action.

21 Sep
09:50

Thomas Le Reun, Benjamin Favier, Michael Le Bars

CNRS, Aix-Marseille Univ, Centrale Marseille - IRPHE UMR 7342 - Marseille, France

Flows driven by elliptical instabilities excited by tides and libration in planetary cores are today considered as viable alternatives of convective flows for explaining turbulence, dissipation and magnetic field generation, for instance in small bodies like the Moon (Le Bars et al. 2011), in Super Earths (Cébron et al. 2012), and even maybe in the Earth (Andrault et al. 2016). While the mechanisms and thresholds for these instabilities are well known (e.g. Le Bars et al. 2015), at least two very challenging points remain to be tackled. First, the saturation process of the excited instabilities remains unknown, giving rise either to large cycles of growth, saturation and collapse, or to sustained bulk-filling turbulence. In the first case, excited inertial modes, once reaching a sufficient amplitude, non-linearly self-interact and give rise to a strong geostrophic flow, which perturbs the rotating base flow and detunes the excited modes, inducing the collapse of the whole resonant scaffolding. In the second case, each of the first resonating inertial modes, once reaching a sufficient amplitude, acts as a seed to non-linearly excite two additional inertial modes, hence priming an energy cascade of triadic resonances. Closely related to this question, a better knowledge of the statistics of the excited turbulence is necessary to understand the energy repartition between the various time and length scales in planetary applications: is this mechanically forced turbulence of rotating turbulence type, of Kolmogorov turbulence type, or of wave turbulence type? The second challenging prospect concerns the magnetohydrodynamics of flows driven by tides and libration. In particular, while dynamo action from elliptical instability has been assumed in several planetary applications, it has up to now effectively been realized only twice (Wu & Roberts 2013, Cébron & Hollerbach 2014). Among the exciting questions still to be answered, one can mention the typical shape of the generated magnetic field (i.e. dipolar or not), the scaling of its amplitude, and the existence of reversals. We will present the latest numerical results of our group regarding those two open questions, combining "global" simulations using the spectral element solver NEK5000 (see e.g. Favier et al. 2015), and "local" simulations using the spectral code SNOOPY, building upon the seminal studies by Barker and Lithwick (2013a,b).

21 Sep
10:20

Elliptical instability in stably stratified fluid interiors.

Jérémie Vidal[1], Rainer Hollerbach[2], Nathanaël Schaeffer[1], David Cébron[1]
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Self-sustained magnetic fields in celestial bodies (planets, stars) are due to flows in internal electrically conducting fluids. These fluid motions are often attributed to convection, as it is the case for the Earth's liquid core and the Sun. However some past or present liquid cores may be stably stratified. Alternative mechanisms may thus be needed to understand the dynamo process in these celestial objects. Turbulent flows driven by mechanical forcings, such as tides or precession, seem very promising since they are dynamo capable. However the effect of density stratification is not clear, because it can stabilize or destabilize mechanically-driven flows.

To mimic an elliptical distortion due to tidal forcing in spherical geometry (full sphere and shell), we consider a theoretical base flow with elliptical streamlines and an associated density profile. It allows to keep the numerical efficiency of spectral methods in this geometry. The flow satisfies the stress-free boundary condition. We perform the stability analysis of the base state using three-dimensional simulations to study both the linear and nonlinear regimes. Stable and unstable density profiles are considered. A complementary local stability analysis (WKB) is also performed. We show that elliptical instability can still grow upon a stable stratification. We also study the mixing of the stratification by the elliptical instability. Finally we look at the dynamo capability of these flows.

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21 Sep
11:00

Precession driven instabilities in the lunar core and the large dissipation at 18.6 yrs.

Dr. Jerome Noir
Institut fur Geophysik

Yoder et al. in 1995 and by Williams et al. in 2001 proposed that the large dissipation in the moon deduced from LLR data at 18.6 yrs period could be buried in a turbulent liquid core. However, at the time they had no arguments to support instabilities developing in the liquid Lunar core to sustain the turbulence. In the present study, we investigate the precession of the spherical rapidly rotating liquid core and demonstrated that shear layers in the bulk can destabilise the flow leading to dissipative small scales motions. Using heuristic arguments, we derive a scaling law for the onset of the unstable regime in good agreement with both numerical and experimental data. Extrapolating these to the moon suggest that the lunar core would be hundred times super critical, hence supporting the hypothesise of precession driven turbulence to account for the large dissipation observed in LLR measurements.

Mechanically-driven flows in ellipsoids. Applications to precession & nutations.

21 Sep
11:30

David Cebron, Jeremie Vidal, Nathanael Schaeffer
ISTerre, Grenoble, France

Planetary and moon fluid layers (cores or subsurface oceans) are mostly triaxially ellipsoidal, sometimes with large ellipticities. For instance, a large surface magnetic field (¿2 micro-Tesla) has been generated in the past on the asteroid Vesta, probably by a dynamo [1] in a strongly deformed [2] liquid core (ellipticity 0.1). This strongly motivates the study of flows and dynamos in ellipsoidal liquid cores, in particular when the mechanical forcing is significant. However, such a study is very difficult. For example, calculating the inertial modes of an ellipsoid has only been achieved very recently [3], and only for a very limited number of modes, whereas it is an important step for weakly non-linear understanding! Building on various recent works [3,4,5], we are now in position to calculate (i) the main flow forced by any mechanical forcing in rotating ellipsoids, and (ii) the (global) stability of this flow, including leading order viscous corrections (without adjustable parameters) [6]. This method allows us to investigate the flow forced by precession in a rigid ellipsoidal liquid core, exhibiting a bistability of the forced flow for certain ranges of parameters [7]. Finally we describe the nutation-driven flow in an ellipsoidal core and study its hydrodynamic stability [8].

[1] Fu et al., Science, 338, 6104, 238-241, 2012. [2] Thomas et al., Icarus, 128, 1, 88-94, 1997. [3] Vantieghem, .Proc. R. Soc. A470: 2014. [4] J. Noir & D. Cébron, J. Fluid Mech., 737, 412-439, 2013. [5] S. Vantieghem et al., J. Fluid Mech., 771, 193- 228, 2015. [6] Vidal et al., in prep. [7] Cébron, Fluid Dyn. Res., 47, 025504, 2015. [8] Vidal et al., in prep.

Instability of precession in an ellipsoid.

21 Sep
12:00

Clément Nobili, Patrice Meunier, Michael Le Bars
IRPHE

Precession has been largely studied in the Earth's core in order to explain the presence of the Earth's magnetic field. This flow has been often modeled as a forcing of the Newtonian fluid of the outer core. Although fundamental studies have focused on the precession of a cylinder, we present here results on the precession of an ellipsoid, which is more relevant to geophysical applications.

Since Poincaré (1910), who gave the inviscid laminar base flow in an ellipsoid, Busse (1968) completed this solution for a viscous laminar fluid. The goal of our study is to describe and understand the inherent instabilities of this particular rotating flow. Indeed, the transition to turbulence has been observed numerically and experimentally but there is no consensus on the mechanisms that should be obtained in real geophysical flows.

The experiment consists in an axisymmetric ellipsoid of ellipticity equal to 0.85, filled with water, whose rotation axis is tilted between 5 and 15 degrees compared to the axis of the rotating table. Qualitative observations have been made using mica particles in a meridional laser sheet. The Ekman number has been varied between 10^{-4} and10^{-5} and the Poincaré number (defined as the ratio between the precession and the rotation frequencies) has been varied over a large range between -0.8 and 0.8.

The stability diagram reveals the presence of different instabilities. A first subcritical instability occurs when the Poincaré solution diverges, in agreement with previous experimental results. A second type of instability occurs near the eigen frequencies of the inertial modes of the ellipsoid.

This ongoing work will be completed by PIV measurements in order to understand the structure and amplitude of the base flow and of the instabilities. We hope that these results will enable the extrapolation of these mechanisms to geophysical flows where the Ekman number and the Poincaré number are very small.

Ref : Poincaré 1910, Busse 1968.

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21 Sep
12:20

Flow driven in the outer core of a precessing planet with an inner core

Raphaël Laguerre[1], Jérôme Noir[2], Nathanaël Schaeffer[3], David Cébron[3], Véronique Dehant[1]

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The dynamics of the liquid core is known to be crucial to the planetary dynamics through angular momentum exchange with the surrounding mantle, kinetic energy dissipation and in some cases dynamo processes. It has been shown that mantle perturbations such as forced precession-nutations, librations can drive complex flows strongly influenced by the rotation in the form of parametric instabilities. In the present study we aim at shedding some light on the influence of an inner core onto the precesssional instabilities. We investigate numerically the flow in the outer liquid core at moderate Ekman numbers (1e-5) driven by the precession of the mantle and the inner core. Following the work by Lin2015, we derive the stability diagram of the flow for a wide range of control parameter. The route to turbulence through resonnance of inertial modes and the possibility of inverse cascade of energy giving rise to large scale vortices in the bulk of the flow are also studied in details.

Lin2015, Y. Lin, P. Marti, J. Noir, “Shear driven parametric instability in a precessing sphere”, Physics of Fluids, 27, 046601 (2015)

Posters

Sensitivity analysis of the transformation between terrestrial - celestial frames. Application to GNSS positioning.

Víctor Puente, Marta Folgueira

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Usage of different reference systems plays a fundamental role in GNSS positioning since the user needs its position in a terrestrial frame while the position solution should be computed in an inertial frame. In this context, it is a common practice to neglect polar motion, nutation and precession effects for the transformation of station coordinates and satellite positions to an inertial frame and to make an approximate transformation based only on Earth's rotation rate in the period of time considered. The aim of this work is to measure the difference caused by this approximation when compared to the rigorous transformation described in IERS Conventions, taking into consideration different GNSS constellations (GPS, GLONASS, Galileo, Beidou), from analytical and numerical perspectives.

IAU Division A - Fundamental Standards.

Catherine Hohenkerk (Chair IAU-SOFA)[1], Brent Archinal(Chair WGCCRE)[2], Brian Luzum (Chair NSFA)[3]

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Standards play an important role in many areas of astronomy. They help to facilitate advances by implementing well-defined practices with associated nomenclature and models. The use of standards provides for the easier exchange of data, data products, and other information; encourages improvements to existing models and future research; and avoids "reinventing the wheel". The International Astronomical Union (IAU) Division A's new Commission A3—*Fundamental Standards*, encourages these activities. This effort involves other Division A Functional Working Groups including Numerical *Standards for Fundamental Astronomy* (NSFA), *Standards of Fundamental Astronomy* (SOFA), and the inter-division A-F Working Group on

Cartographic Coordinates and Rotational Elements (WGCCRE), all of which involve the relevant experts. Commission A3 and these working groups collaborate with the wider community to draw together the information and data, to make the appropriate choices, and importantly ensure that their IAU standards are understood and are widely available. This poster highlights these groups and their work.

Speaker Index