EARTH ROTATION DYNAMICS AND GEOPHYSICAL FLUIDS

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INTRODUCTION

The IERS efforts to coordinate the monitoring of Atmospheric Angular Momentum (AAM) have been very successful. The purpose here is to consider whether the efforts should extend to other geophysical fluids, such as the oceans, core, and groundwater. We propose that this extension is appropriate and necessary to fulfill the fundamental missions of the IERS, but that any newly proposed activities should not adversely impact the current ones by diluting existing resources. Furthermore, extensions of IERS activities should use existing services (as for instance, the FAGS services); and, existing special study groups (SSG) or existing working groups (WG) should not be overlooked. We are persuaded that there are competent existing services from which the IERS would gain, but that there is probably not enough exchange with the IERS. There, the IERS can play a pioneering role by creating and appointing coordinators acting as link-agents, who bridge the information towards the IERS or towards other bodies. These persons should have a background which permits them to understand the interests of the two bodies.

On the other hand, if there is no competent service or WG or SSG capable of answering particular points addressed by the IERS, then it may be worthwhile creating this activity within the frame of the IERS in the form of a new sub-bureau (SB) or coordinating center (CC). The success of a SB or CC will depend critically on the level of activity and interest of the individuals. Careful selection should lead to little additional work for IERS personnel. Delay in establishing a center may be preferable to an early effort that lacks sufficient level of interest and commitment.

In this report, one will find suggestions to create a new sub-bureau (SB) or coordinating center (CC), as well as sub-sections (that we also call sub-bureaux in the text) of this SB or CC, i.e. we consider an extension of the present Sub-Bureau for the Atmospheric Angular Momentum. This extension could be seen as considering the SBAAM as a sub-section of the new CC (which could be at the same location). In this report, we discuss the necessity of an extension, but we will not discuss the structure itself, neither the incorporation of this structure as part of the present IERS structure. This is discussed in the report related to Topic 1.

A long term goal of the IERS effort should be to make issues and data related to global scale geodetic quantities, Earth's rotation, and reference frame, more visible within the Earth Sciences Community. We should have as a goal that all those who model geophysical fluids (atmosphere, ocean, core fluxes, mantle convection fluxes, ice, snow, ground water) will be concerned with, and examine the performance of their model using predictions of geodetic quantities such as nutation, LOD (length-of-day) and polar motion. That is, we want scientists outside the IERS to consider geodetic quantities as useful measures. This is the case, for instance, for geodetic measures related to some parameters relevant to the SEDI (Study of the Earth Deep Interior) community, as well as for geodetic measures related to global climate quality which should be considered just as temperature, pressure, rainfall, etc are normally.

Assessment of current mission: users of, requirements for and access to AAM.

There is no doubt that the AAM computations should be continued. The availability of estimates from numerical weather prediction models of the atmosphere's angular momentum has enabled a wealth of scientific investigations and contributed to improve tracking and navigation of interplanetary spacecraft. The Sub-Bureau for Atmospheric Angular Momentum (SBAAM) has played an important role in these endeavors by being an advocate for the estimation of AAM by the various operational weather prediction centers and by collecting, archiving, and disseminating the AAM estimates. At present, the angular momentum of the atmosphere about three axes, related to the excitation of Earth rotation and polar motion, is computed and provided on a near-real time basis by the U.S. National Centers for Environmental Prediction (NCEP, formerly NMC, the National Meteorological Center). The sub-bureau also acts to collect and distribute AAM data from other large world meteorological centers. Both analysis and forecast values are treated in this way. These activities constitute important missions of the SBAAM. For a complete description of the SBAAM activities, see Annex 1.

Since AAM can be expected to continue to play a key role in future Earth rotation studies, the present activities of the SBAAM should not only be continued but might be expanded upon. Some thoughts in this area have been discussed and transmitted directly to the SBAAM. They are summarized as follows:

(1) new meteorological data and parameters could be added,

(2) not only AAM approach but also the torque approach should be considered,

(3) new atmospheric data centers must be included,

(4) combination of AAM estimates would be useful,

(5) extended period of AAM estimates would also be useful,

(6) the impacts of the atmosphere on precession-nutation should be computed,

(7) in order to improve the availability of the SBAAM data, a ftp-system should be implemented,

(8) together with more documentations.

Note that some of the recommendations are already underway or done. The SBAAM is providing an important service to the scientific community and deserves greater recognition. These suggestions should not be taken as criticisms but rather as constructive comments designed to enhance the strength of the SBAAM. Possible mission extension: should IERS take some part in the coordination of the monitoring of global fluids (terrestrial water, ocean currents, core currents) ?

Given the success of the sub-bureau for AAM, we consider whether other sub-bureaux should be created for quantities such as ocean angular momentum (OAM), ocean tidal angular momentum (OTAM), or core angular momentum (CAM). If such sub-bureaux were to be created, what would be their role, who would be the leaders, and who would be their customers? One difficulty we see here is that unlike AAM, no operational centers exist for the computation of OAM, OTAM, or CAM. In the case of AAM, operational weather prediction centers running atmospheric general circulation models already existed when the SBAAM was created. Thus, there was a role for a sub-bureau to collect the AAM values produced from the products of these existing operational weather prediction centers. This is not the case for OAM, OTAM, or CAM where the ocean general circulation, ocean tides, and core flow models, respectively, are run by research rather than operational groups. Is this distinction important? Is it appropriate for the IERS to advocate, collect, and archive quantities from research rather than operational groups?

We think that the distinction between collecting quantities from research rather than operational groups is important when discussing what the role of such sub-bureaux should be, but not in discussing whether or not such sub-bureaux should be created. We think that it would be a service to the research community to have such sub-bureaux advocating, collecting, and archiving OAM, OTAM, and CAM, and hence we would encourage the IERS to expand in this direction by creating such sub-bureaux, even though their only customers will be from the research community. (The customers of the SBAAM include not only research groups but also operational groups.) However, since the sub-bureaux for OAM, OTAM, and CAM will be collecting results from research rather than operational groups, they will need to be more aggressive in their role. Since the SBAAM collects results from operational centers, once the collection mechanism has been initiated, it can passively and automatically archive the results as they arrive. However, sub-bureaux for OAM, OTAM, and CAM must establish and maintain active contacts with the relevant research groups in order to ensure that the OAM, OTAM, and CAM are computed and sent to the sub-bureaux every time the ocean general circulation, tide, and core flow models are run. Thus, organizations willing to support such active sub-bureaux must be found if they are to be established. We give in Annex 2 some propositions for these eventual sub-bureaux. We give there the main tasks (the list is probably not exhaustive) that we see for the SBOAM, SBOTAM, and SBCAM, as well as for additional ones like the sub-bureaux for geocenter and gravitational field, or for water vapor, or for ionospheric TEC.

The next question we see is: should separate sub-bureaux for OAM, OTAM, and CAM be established, or should they and the SBAAM be combined into, say, one sub-bureau for Angular Momentum (SBAM)? If combined into one overarching sub-bureau, would all its parts need to be at the same hosting organization, or could its subparts (sub-sub-bureaux?) be located at different organizations where the relevant expertise resides? If separate sub-bureaux are established, we suggest that each have World-Wide Web homepages through which their archives can be accessed by anonymous ftp and with hot links to each of the other sub-bureaux homepages as well as with the IERS homepage. Thus a virtual SBAM can be created from geographically separate groups. Geophysical fluid monitoring pertaining to nutations.

We give in Annex 3 a description of the scientific situation concerning nutations. We summarize here the conclusions:

(1) It is absolutely necessary to continue VLBI observations. There, the proposed new VLBI/CORE continuous measurement of Earth rotation with the anticipated improvements in precision and temporal resolution would play an important role.

(2) There is also an important effect of the atmosphere on nutations. It is thus necessary to collect, archive and disseminate values of the x- and y- components of the AAM and/or values of the x- and y- components of the atmospheric torques acting on the Earth. Because nutations are quasi-diurnal in the TRF, short time intervals and long time span are necessary. Not only the effects at particular forced nutation frequencies should be considered, but also eventual excitation of Earth normal modes. Another interesting extension is to compute the effects of the atmosphere on sub-daily polar motion and prograde diurnal polar motion (retrograde diurnal polar motion corresponding to nutation).

(3) The ocean tide effects due to ocean heights as well as the ocean currents have a contribution to nutations far above the observational standard deviation. Thus, a SB or a CC or a coordinator for OTAM would be helpful. The situation is somewhat different compared to the atmosphere, because models rather than an operational unit are the basic tools. However the models are constantly evolving, requiring communication to the IERS and new calculations of geodetic effects.

(4) Mantle mass anomalies and the associated boundary displacements might play an important role in the nutation phenomena. Here, the observed precession and nutation can produce numerical values of parameters useful for the seismic community.

Recommendation - Propositions

This discussion contains suggestions to establish coordinators or eventually sub-bureaux (or coordinating centers) for OAM, OTAM, CAM, geocenter variations, gravitational field models, and water vapor, and ionospheric TEC, all of which would greatly expand the scope of the IERS. If capable host institutions can be found for the suggested new coordinating centers (or sub-bureaux), then we suspect that the IERS can absorb these new sub-bureaux fairly easily. However, the new activities should in no way jeopardize the quality of the existing IERS programs which have been extraordinarily successful in providing timely and accurate data on Earth rotation, and in establishment and maintenance of terrestrial and celestial reference frames.

Summary of recommendations

(1) keep SBAAM and make recommendations for strengthening this SB;

(2) examine currently existing organizations dealing with geophysical fluids, seeking existing data and computational models such as numerical and/or hydrodynamical ocean models; this could be done by the use of existing WGS or SSGs, or by nominating a coordinator, or by calling for a new coordinating center (or sub-bureau); this organizer or organization would create coordinated links with relevant bodies or research groups, eventually within a larger organization;

(3) create a SB or a CC for angular momentum related to geophysical fluids pertaining to the Earth orientation parameters as well as any parameters relevant for the space geodesy technics; this SB or SB would deal with different sub-SB or sub-CC;

(4) create a www page and links to associated ftp sites for the IERS and AM-related sub-bureau.

Annex 1 - Description of the current activities of SBAAM

The meteorological data used in SBAAM calculations consist of motion terms, calculated from the wind vector (zonal wind and meridional wind) and the mass term, calculated from the surface pressure of the atmosphere. Integrations to different vertical levels in the atmosphere may be available. The above data are typically available on a six-hourly basis, which usually makes diurnal signatures evident. The most complete vertical extent of the data spans the atmosphere between 10 and 1000 hPa, or approximately 99% of the mass of the atmosphere.

The approximate effect of the ocean mass redistribution is considered in the calculations of AAM by the inclusion of two options: modeling with either a perfect inverted barometer or with the total absence of an inverted barometer relationship. Because indications are that the true nature of the atmosphere/ocean relationship falls somewhat in between these two options, the investigation of alternate approaches to the inverted barometer issue is most appropriate, including the use of ocean dynamic models. Other quantities, related to the global momentum of the atmosphere, are values of the zonal mean wind, zonal mean temperature, and spherical harmonics of surface pressure, all of which can be calculated from the reanalysis fields.

Recently data from a historical atmospheric "reanalysis" has become available to calculate angular momentum for historical periods, starting in the mid-80's to the present, but eventually to include one or two decades earlier. Within the meteorological community, these efforts are designed to incorporate any data not included in the original operation results, but also to perform the computations with a fixed numerical scheme. Such series are more continuous, and are available to those users who wish to study the atmospheric component of the Earth's dynamic system, momentum exchange with the solid Earth and the ocean, and the momentum as a climate parameter. Angular momentum studies of these reanalysis data sets should lead to understanding processes on a number of time scales, including those on interannual, seasonal and intraseasonal.

Annex 2 - Scientific activities pertaining to IERS and related to possible sub-bureaux.

(1) Ocean Angular Momentum. One very interesting extension we see for the IERS is to create a SBOAM (Sub-Bureau for Ocean Angular Momentum). A separate group dealing specifically with tides is discussed below. Indeed, the role of the oceans in Earth rotation, after the effects of the atmosphere, is important, particularly for short time scales (subdaily and daily periods) as well as medium time scale (daily to yearly periods). The data-poor oceans have delayed an "operational" oceanography modeling program relative to meteorology, but we believe things are moving quickly towards use of models and data assimilation as is currently done for the atmosphere. There have been many groups that have turned out preliminary results for OAM based on oceanic General Circulation Models (GCM). Model results indicate observable effects on the LOD, and substantial contributions to the excitation of seasonal polar motion; at shorter time scales, oceanic excitation can be as important as atmospheric excitation. Both mass redistributions and fluctuating currents contribute importantly to variability in OAM. While the inverted barometer approximation has been the focus of previous OAM calculations, in reality, the issue is much more complicated, involving also wind forcing and oceanic currents, and a proper accounting will require the use of oceanic numerical models. As we approach operational capabilities for OAM prediction, a sub-bureau should be in place to provide information to the IERS. Possible future operational centers include US Navy, NCEP, and NASA Goddard Space Flight Center.

(2) Ocean tidal angular momentum. Most early works have been based on Schwiderski's tide model, but Topex/Poseidon (T/P) diurnal/semidiurnal tide models, or oceanic hydrodynamic models are now available. However, there are still some important tidal waves missing in these computations, for instance, in the diurnal frequency band, the psi_1 wave is important because it is near the Free Core Nutation (FCN) Resonance, but it is not determined in present ocean models. Continued refinement of tide models is expected with present and future altimetry missions. A coordinator position for tide models and angular momentum predictions seems

appropriate. There is no comprehensive method for observing global tidal currents in the way that altimetry now observes elevations. Thus, dynamical assumptions about the ocean will always play an important role, either in purely hydrodynamic models or in models that attempt to combine elevation (and possibly current) observations with theory. Assimilation methods that bring out explicitly this combination of data and theory and allow for quantitative testing of dynamical assumptions are an important development. Already, however, the NASA Goddard group have shown that the new Topex/Poseidon ocean tide models are in better agreement with Earth-rotation measurements than earlier models, including the pioneering estimates from the Brosche/Seiler model predictions. The agreement for eight major tidal components (4 diurnal and 4 semidiurnal) between T/P model predictions and long-term Earth rotation observations is remarkable, both in amplitude an phase. In fact, the T/P models can explain as much as 90% of the observed sub-daily variance in UT1, and about 60% variance in polar motion, during the intensive VLBI Earth rotation measurement campaign CONT94. This success paves the way for further study of non-tidal excitations sources, such as AAM, OAM, Earth libration, and atmospheric thermal "tides". A breakthrough can be anticipated with the proposed new VLBI/CORE continuous measurement of Earth rotation with the anticipate improvements in precision and temporal resolution. In addition the ocean tide effects due to ocean heights as well as ocean currents make a contribution to nutations far above the observational standard deviation. Thus, a SB or a CC or a coordinator for OTAM would not only be helpful for Earth's rotation but also for precession/nutation. The situation is somewhat different compared to the atmosphere, because models rather than an operational unit are the basic tools. However, the models are constantly evolving, requiring communication to the IERS and new calculations of geodetic effects.

(3) Terrestrial water (ground water, snow, and ice). There have been some calculations on the effect of continental water and on the effect of man-made reservoirs and underground water storage. All these estimates are quite uncertain, incomplete, and suffer from lack of global data, but all suggest that water storage on land, in its various forms, produces observable polar motion and variations in other geodetic parameters such as center of mass and station coordinates. While the present data are poor in quality and coverage, the inclusion of the water cycle in global climate and general circulation models is underway, meaning that in the near future we should expect assimilated model predictions of soil moisture, river discharge, snow and ice cover, and change in underground storage, which should permit more accurate estimates.

(4) Core angular momentum. There appear to be clear correlations between variations of the length-of-day at decade time scales and the parameters of the geomagnetic field. The link can be explained by the fact that the core velocity field and the magnetic field are directly related one another, and that the core angular momentum, related to that velocity field, is transmitted to the mantle. The mechanism for transferring core angular momentum to the mantle (coupling at the core-mantle boundary) is uncertain. It has been suggested that the main mechanism is a topographic coupling (also called pressure torque or mountain torque; core fluxes pushing on the bumps of the Core-Mantle Boundary (CMB)). Early numerical studies predicted a torque which is about 50 times too large, although recent revisions accounting for an additional gravitational torque have reduced the discrepancy to only a factor of 5. The other possible mechanisms of core-mantle coupling are viscous coupling or electro-magnetic coupling at the CMB. The core situation remains uncertain for several reasons: the models predicting the bumps are incomplete, the connection between surface magnetic observations and the CMB field is uncertain, the theoretical approximations like geostrophy, may be inappropriate, and the core viscosity is not well known. The geomagnetic community is active, and interested in these matters. The recent numerical simulations of the geodynamo and the seismological discovery of an inner core rotation should stimulate interest in the geomagnetic community to interact with the IERS.

(5) Geocenter and gravitational field. Satellite techniques such as SLR and GPS can, in principle, determine the location of the Earth's geocenter which will vary in response to Earth system mass fluxes, and hence analysis of geocenter variations provides information about these mass fluxes. Thus, in principle a sub-bureau to advocate, collect, and geocenter determinations would provide a service to the research community and we suggest that one be established. However, care must be taken to ensure that the quantities being archived are properly

documented so that users know how they were determined. Geocenter studies are still in their infancy and many questions have not yet been resolved. Numerous organizations produce global gravitational field modelsparticularly of the static field, but also of time-varying components of the field. Accurate static gravitational field models are required for a number of reasons, not the least of which are satellite missions such as altimetry and Synthetic Aperture Radar (SAR) Interferometry. Having an archive of the available gravitational field models would be a service to the user community by providing "one-stop shopping" for them. Time variable gravity and geocenter variations can both be computed in principle from the same air and water surface load variations used in angular momentum calculations. The gravity and mass center variations involve simply other surface integrals (spherical harmonics). Hence we suggest that a simple extension of activities related to angular momentum would be to calculate other spherical harmonics of mass load variations (air and water), besides those related strictly to angular momentum.

(6) Water Vapor (Zenith Path Delay). Radiometric techniques such as VLBI and GPS (and DORIS, PRARE, ...) routinely estimate the zenith path delay of radio signals through the atmosphere. These path delay estimates are a function of the weighted temperature and water vapor content of the atmosphere and hence may provide important measurements for climate and weather prediction models, especially of the integrated water vapor. The results are important to geodetic measurements, specifically to the problem of correcting Synthetic Aperture Radar (SAR) Interferometry data, as well as to climate and weather studies. Additional GPS occultation results (as in GPS Met) are available and likely to be more prevalent in the future (The GPS Met satellite is in orbit now and is operated by UCAR/UNAVCO/JPL. It uses the GPS signals observed from a low-orbit satellite to measure travel time delays through the atmosphere, providing a very uniform measure for the whole earth of 'limb soundings' or occultation measurements giving temperature/water vapor. It is very complimentary to the ground based solutions from GPS or VLBI because it provides a vertical profile through the atmosphere, whereas the GPS or VLBI results are a vertically integrated profile.). Because path delay data are of interest in geodetic observations, as well as to a wider community, this is an area of possible study and coordination by the IERS. However this must be closely coordinated with related activity by the IGS, perhaps via a joint IERS/IGS sub-bureau established for this purpose.

(7) Ionosphere TEC (Total Electron Content). An additional aspect of the atmosphere that is of interest for radio-signal analyses is the Total Electron Content (TEC) of which abnormal values can largely perturb the measurements. This is particularly important for the near future because we are now in a minimum of the solar activity which will increase rapidly in a couple of years. In addition, ionospheric perturbations as scintillation effects and Traveling Ionospheric Disturbance (TID) produce irregular variations in the signals and consequently in the deduced quantities as station position vectors. On the other hand, the TEC can be deduced from radio-signal observations and abnormal behaviours of the atmosphere can be pointed out. These observations are important for the ionosphere scientific community. Because the ionosphere state is important for the geodetic community as well as the atmospheric community, this is also an area of possible coordination of IERS. As for the water vapor, this must be closely coordinated with related activities in IGS.

(8) Mantle fluxes. Mantle convection induces mass heterogeneities inside the mantle (as well as associated mass anomalies every where else). Down going slabs associated with plate tectonics are part of that process. These mass anomalies induce spatial variations in the gravity field at the Earth's surface, which is important for satellite geodesy. Mass heterogeneities also induce variations in the Earth's moments of inertia, and thus in the global dynamical flattening. This parameter can also be derived from the observation of precession. The comparison of both kinds of measures can lead us to a better knowledge of the Earth's interior, of the precession constant, of the plate tectonics, and of the gravity field. There is a second parameter related to mantle convection and which is of great importance for nutations, the core flattening. Indeed, the core flattening is one of the parameters which enter the equation for the Free Core Nutation. The FCN is an Earth's normal mode related to the fact that one can excite an angle between the instantaneous rotation axis of the core and the instantaneous rotation axis of the mantle. Precise

VLBI measurements (as well as precise tidal measurements by using superconducting gravimeters) can be used to derived the "observed" value of the FCN from the induced resonance in the Earth's response. The observed value that is deduced from the combined data is 434 sidereal days in inertial space, while the value associated with the adopted IAU 1980 nutation is 460 days (this value is associated with a spherical Earth uniformly rotating initially in hydrostatic equilibrium). A small increase of the core flattening corresponding to an increase of the core equatorial radius with respect to the polar radius of only about 500 meters would explain this difference. Here, mantle convection can play an important role is refining this explanation. Indeed, the CMB displacement associated with the mantle convection fluxes are in agreement with an increase of the core flattening, and so, a decrease of the FCN period. Here, because mantle convection lateral heterogeneities are not yet precise enough for geodesic observation (we would need to know the CMB boundary displacement at about a few meters for instance), the seismic community can benefit from the constraints derived from VLBI precession/nutation observations.

Annex 3 - Scientific description and examination of the geophysical fluids pertaining to nutation.

Theoretical models for nutations are at a crossroads, because observations are now accurate enough to observe interesting discrepancies with existing theories. Among the important problems are: the "geophysical nutations" which are called like this because they are particularly sensitive to changes in the Earth's transfer function (as the 18.6 year nutations for instance), and the value of the precession constant. For example, if one considers a theoretical constraint on the relation between the 9.3 year, the 18.6 year nutations and the precession, one obtains a correction to the precession constant (derived from the IAU 1976 adopted precession and discussed in the WG report on the nutation model adopted by the IAU in 1980) of -3.1 mas/year. If we do not use the constraint, we obtain -3.0 mas/year. This illustrates the necessity of continuing the observations of the nutations to understand long period nutations. There are also differences at the level of tenths of mas in the 13.66 day nutation among different observations, and peaks in the residual spectrum at 5 and 7 days. There is an effect of the atmosphere on the prograde annual nutation, as well as an excited FCN above the standard deviation of the observations. These effects need to be observed. All of these questions emphasize the need to continue VLBI observations for both short and long period nutation studies. There is no good link between the terrestrial and celestial reference frames if the nutations are not accurately determined, and to that aim, it is absolutely necessary to continue the VLBI observations. Activity within the VLBI community to organize effectively continuous observations is encouraging and important. A. Effect of the atmosphere

(1) For atmospheric fluctuations, most operational numerical weather prediction centers already submit to the SBAAM, AAM values computed at 6-hour intervals. The GSFC DAO reanalysis has provided products as often as every 3-hours, and even hourly values are possible. Close cooperation with the modeling groups, a future focus of the SBAAM, can thus provide the basic data to calculate atmospheric contributions.

(2) There is an important impact of the atmosphere on the nutations, in particular, on the prograde annual nutation. There are differences between the most recent theories and the observations at the level of the tenth of milliarc second (mas). This is above the noise of the observations (some hundredths of mas). The SBAAM already archives the data needed to compute atmospheric effects on nutation, namely, the x- and y-components of the AAM (wind and pressure terms separately) at 6-hour intervals. It would be easy to extend the work of the AAM sub-bureau by computing the effect from the first and second components of the angular momentum of the atmosphere on the nutations. A torque approach has been used by several authors, but they only computed by using spherical harmonics expansions. These torques are not only the pressure torque acting at the Earth surface, but also the gravitational torque (which is counterbalancing an important part of the pressure torque) and the friction torque (which is very small). The resulting torque predicts effects on nutation which are too large with respect to the differences between the recent geophysical nutation theories and the observations.

(3) There could be an important atmospheric effect at the K_1 sidereal diurnal frequency. This is related to the atmospheric excitation at the one-solar-day period modulated by an annual period and which gives then a one-sidereal-day period (K_1) in the terrestrial frame. There is a corresponding impact on the precession. The atmospheric pressure torque acting on Earth gives an effect of a few mas/year. Again the pressure torque is not the only one acting on the solid Earth, the gravitational torque and the friction torque are supposed to decrease it (again probably one order of magnitude). Nevertheless, even for one order of magnitude less, this could be important for the determination of the general precession, the precession constant and the Earth dynamical flattening.

(4) In the observations there is some energy around the Free Core Nutation (FCN) period. It is thought that there is an excitation of this normal mode. While it is probably not possible to explain it entirely from a purely luni-solar excitation, it is suspected that it is excited by the atmosphere because there is sufficient energy in the broad-band variability of the atmosphere to excite it.

(5) It has been shown from intensive VLBI campaigns that the semi-diurnal and diurnal polar motion (the retrograde part corresponds to the nutations) can be obtained. While this is thought to be related to the oceans, it is suspected that there is an atmosphere-ocean interaction. See next point.

Summarizing these points, an important extension for the AAM-sub-bureau would be to compute the effects of the atmosphere on the nutations. The SBAAM already archives the basic data needed to compute atmospheric effects on nutation, namely, the x- and y-components of the AAM (wind and pressure terms separately) at 6-hour intervals. This is not a simple matter and will need a lot of additional input mainly because nutations are usually studied in the frequency domain. Another interesting extension is to compute the effects of the atmosphere on sub-daily polar motion, and on prograde polar motion, although it is generally believed that the oceans are responsible for an important part. B. Effect of the oceans.

(1) Ocean heights: The Wahr and Sasao (1981) corrections for the effects of the ocean heights on the nutations have become the accepted method but have not been adopted by the IAU. The ocean effects are not completely described by this approach because the currents may indeed play an important role, as discussed below. Wahr and Sasao used Schwiderski's ocean tide models but since then, the Topex/Poseidon mission has produced many new ocean tide models derived from satellite altimetric data, ocean loading effects gravity data, finite element modeling and/or on ocean hydrodynamics. Validation and testing of these models can be coordinated with other FAGS services as the ICET (International Center for Earth Tides). The Topex/Poseidon community has also devoted much work to validation of these new tidal height models, primarily because of their crucial role in other oceanographic investigations that use altimetry. In the open ocean, the new T/P models have been shown to be significantly more accurate than any models existing before 1992. These conclusions rely on comparisons to in situ tidal observations with island gauges and with ocean-bottom pressure recorders, as well as on variance-reduction tests with independent altimeter data (e.g., Andersen *et al.*, 1995; Shum *et al.*,1996). The story, however, is somewhat different in shallow and marginal seas. In such areas, the tides are spatially very complex, and the large spacings between altimeter ground tracks have precluded any great improvements. Because the tides in these areas are also large, they may alias into spatial harmonics that cause nutation. Thus, there is still important work to do in improving tidal elevation models in shallow seas.

(2) Ocean currents: Some authors have already computed the effects on the retrograde diurnal polar motion using the angular momentum approach, finding the currents to be as important as the heights (or maybe a little bit less). It would be valuable to compute currents from Topex/Poseidon or other recently available ocean model mentioned above. The corresponding effects on nutations are above the noise level of the observations for some of the geophysical nutations and need to be incorporated. In summary, the effect of ocean tides on the nutations deserves the attention of a sub-bureau or coordinator of OTAM to collect and archive the angular momenta carried by the diurnal tidal currents and height changes. The situation is somewhat

different compared to the atmosphere, because models rather than an operational unit are the basic tool. However the models are constantly evolving, requiring communication to the IERS and calculations of geodetic effects. C. Effect of mantle convection.

We may consider the mantle to be another geophysical fluid that plays an important part in the nutations. The mantle undergoes convection, implying that the Earth's interior properties are not spherically symmetric, but the Earth contains mass anomalies: there are places in the mantle where the density is high (where there is a mass accumulation producing down-going motion) and places where the density is low (there is a mass deficit associated with upwelling). This induces variations in the moment of inertia and consequently of the computed dynamical flattening. There is a difference between the dynamical flattening derived from the observed precession and the one derived from the hydrostatic equilibrium of the Earth based on the spherical properties given by seismologists. Here the IERS can not benefit yet from the seismic observations which are not yet well constrained in the lower mantle and at the 670 km depth (boundary between the lower mantle and the upper mantle), but rather can give some constraints to the seismologists as the observed dynamical flattening of the Earth. The VLBI nutations can also be used to derive the FCN period from the resonance effects that the FCN induces in the forced nutations. An increase of the core flattening corresponding to an increase of the core equatorial radius of about 500 meters is proposed for explaining the difference between the observed and the computed FCN periods. This could also be used as a constrain for the seismological models of the Earth's interior.