Joint Discussion 7

Session 1   Theoretical aspects of reference systems (Sergei Klioner, chair)

1.01.   Relativity in fundamental astronomy: status and prospects

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Invited

First the scope of 'Relativity in Fundamental Astronomy' is discussed. The main subjects are: Astronomical space-time reference systems, celestial mechanics, astrometry and metrology. For each of these subjects the current status of relativistic concepts and models with their intrinsic accuracies are discussed and confronted with accuracies needed in fundamental astronomy in the near future. Model deficiencies are identified and future work for Commission 52 (RIFA) is suggested.

1.02.   Celestial dynamics and astrometry in expanding universe

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Invited

Post-Newtonian theory of motion of celestial bodies and propagation of light was instrumental in conducting the critical experimental tests of general relativity and in building the astronomical ephemerides of celestial bodies in the solar system with an unparalleled precision. The cornerstone of the theory is the postulate that the solar system is gravitationally isolated from the rest of the universe and the background spacetime is asymptotically flat. The present talk abolishes this postulate and lays down the principles of celestial dynamics of particles and light moving in gravitational field of a localized astronomical system embedded to the expanding universe. We formulate the precise mathematical concept of the Newtonian limit of Einstein's field equations in the conformally-flat spacetime and analyse the geodesic equations of motion of particles and light in this limit. We demonstrate that the equations of motion of particles and light can be reduced to their Newtonian counterparts by doing conformal transformations of time and space coordinates. However, the Newtonian equations for particles and light differ by terms of the first order in the Hubble constant. This leads to the important conclusion that the equations of motion used currently by Space Navigation Centres and Astronomical Observatories for calculating orbits of celestial bodies, are incomplete and missing some terms of cosmological origin. We explicitly identify the missing terms and demonstrate that they bring about a noticeable discrepancy between the observed and calculated astronomical ephemerides. We argue that a number of observed celestial anomalies in the solar system can be explained as caused by the Hubble expansion of the universe.

1.03. Extension of the DSX-formalism to 2PN order for the problem of light propagation

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The well known Damour-Soffel-Xu (DSX) formalism of relativistic celestial mechanics and astronomical reference systems is restricted to the first post-Newtonian (1PN) approximation of Einstein' s theory of gravity. The key features of the DSX-formalism are: the use of N+1 different coordinate systems for the description of the gravitational N body problem and a special canonical way of writing the metric tensor in these N+1coordinate systems; introducing the potentials (w, W) and vector potentials (w^i ,W^a) to describe the metric tensor in global coordinates (small symbols) and in the local coordinate systems where the metric potentials satisfy linear equations and separating W and W^a into internal and external parts in every N local coordinate systems. The internal part is determined by local gravitational sources (Blanchet-Damour (B-D) multipole moments) and the external part can be determined by matching the metric tensors in the global and the local system. It is the purpose of this work to extend the DSX formalism to include also certain terms of second post-Newtonian (2PN) order. Since one main field of application will be high-precision astrometry only the spatial part of the metric tensor will be modified to correctly describe the propagation of light-rays to 2PN order, considering also terms of order c^{-6}. In this way new potentials (q^{ij}, Q^{ab}) appear in the global and local metric tensors. These new potentials are related with the DSX metric potentials and the energy-momentum tensor and also satisfy linear equations. Here it should be emphasized that the introduction of q^{ij} and Q^{ab} does not influence the relations and equations for the metric potentials, i.e., they do not destroy the spirit of the DSX formalism in our extension. As well as in the DSX formalism Q^{ab}can be separated into an internal part Q^{+ab} and an external part, ^{ab}. The Q^{+ab}- terms in a local system will be related with the B-D mass-multipole moments of the body under consideration and a set of new multipole moments related with the shear-stresses inside the body. The relation between ^{ij} and ^{ab} can be also deduced from a matching condition and the spatial harmonic gauge condition. One rather complex situation is that the external super-potential term appears in the inhomogeneous term of the linear relation between ^{ij} and ^{ab}. The transformation rules for the new potentials from the local to the global frame will be derived. In this way the modified global metric tensor will be obtained. Even for a system of mass monopoles the global spatial metric will contain additional terms to the Einstein-Infeld-Hoffmann metric (from which the EIH-equations can be derived), the ^{ab} terms. Consequences of these ^{ab} terms for light-propagation are studied by analytical estimations and numerical integration of the light-ray (null geodesics) equation. Although there are many papers devoted to the problem of light propagation to 2PN order, but none of them has discussed the

problem in N+1 coordinate systems. Our work is the first complete discussion on the problem of the light propagation in the 2PN order within the frame of N+1 coordinate systems.

1.04. A dynamical reference frame for geophysics and experimental gravitation

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A constellation of satellites equipped with inter-satellite links naturally realizes an autonomous relativistic positioning system. Given the dynamics of the constellation of satellites, it is possible to define a spatio-temporal dynamical reference frame anchored to the constellation: the ABC (Autonomous Basis of Coordinates) reference frame. This reference frame is independent from all other systems, and thus could help to refine these others systems. As it is based on well known satellite dynamics, it is highly accurate and stable. It will open new possibilities in geophysics: aiming for absolute positions of markers on Earth at sub-millimeter accuracy, it would be possible to study the interior structure of Earth, continental drifts, ocean currents, geopotential differences and maybe earthquake prediction. The constellation of satellites probes the geometry of space-time, acting as a gravimeter. The link of the ABC reference frame with other reference frames will help to understand how the local geometry is embedded in the global arena of space-time. Finally, applying this concept to far-away clocks (e.g. pulsars) will open new possibilities for solar system navigation.

1.05. Observational evidences for the propagation speed of gravity from Earth tides

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Gravitational field is the only universal force which constrains the existing and moving ways of everything in our universe. There are several contradictious ideas on the propagation of gravity. Newton's law of gravitation is a theory of instantaneous action at a distance (IAD model); it believes that the speed of gravity is infinite. Einstein's relativity assumes that the speed of the gravity should be finite, and the gravitational waves travel at the speed of light. However physicists have not yet found any reasonable method to measure the propagation speed of gravity. Here we show direct observational evidences to prove that the gravity travels at the speed of light. Tang found that the current model of the Earth tide implies a hypothesis that the gravity travels at the speed of light (TSL model), because the positions in the model are apparent positions; by comparison among the theoretical models and the observation curves, we further found that TSL model is very close to the observations, and IAD model is relatively far away to the observations. Furthermore, we have solved the propagation equation of gravity derived by Tang, with the observation data of Earth tides from Tibet and Xinjiang of China, after the correction of phase lag due to inelasticity of the Earth, and found that the speed of gravity is 0.96 to 1.09 times the speed of light with relative errors of about 5%. It may provide strong evidences to show that the speed of gravity is the same as the speed of light.

1.06. Explicit expressions for the global metric and coordinate transformation with local multipole moments

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The development of techniques might bring the subtle effects due to post-Newtonian multipole moments into the threshold of measurements in some future experiments. It inspires us to expand the integrals in the global metric and the transformations between the global and local coordinates and make them explicitly depend on the local multipole moments as a small step to bridge the gap between the theory of reference frames and future practice.

1.07. New approach to relativistic celestial reference frames

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The current IAU recommendations regarding relativistic reference frames are mainly based on the works of Brumberg and Kopeikin on one hand and Damour, Soffel and Xu on the other hand. However the current recommendations give the transformations between the barycentric and the local frames in one way only, while both direct and inverse transformations are needed, at least for completion, if not for practical purposes. In our work, we (S. Turyshev, V. Toth and I) give an alternative approach to the two previous ones considered in the IAU resolutions. Conversely to those, our method is not based on the so-called matching technique. Our main result lies in the fact that we got both the direct and the inverse transformation at the same time – allowing checking the consistency of both transformations. Here we describe the simple case with monopoles as sources. The full extended-bodies case will be presented elsewhere.

1.08. 2PN light propagation in the scalar-tensor theory: an N-point mass case

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Within the framework of the scalar-tensor theory, its second post-Newtonian (2PN) approximation is obtained by Chandrasekhar's approach. By focusing on an N-point mass system as first step, we reduce the metric to its full 2PN form for light propagation. We find that although there exists two parameterized post-Newtonian (PPN) parameters gamma and beta in the 2PN metric, only gamma appears in the 2PN equations of light. As a simple example for applications, a gauge-invariant angle between the directions of two incoming photons for a differential measurement is investigated after the light trajectory is solved in a static and spherically symmetric spacetime. It shows the deviation from the general relativity $\delta\theta$ does not depend on beta even at 2PN level in this circumstance.

1.09. Relativistic Spherical Multipole Moments in Astronomy

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In this paper, a simple and reasonable relation between relativistic Cartesian and spherical multipole moments with harmonic gauge in the post-Newtonian framework is presented. How to define the time slowly-changing relativistic spherical multipole moments is investigated and discussed in detail. And with these multipole moments, the equations of motion of celestial body and photo are derived. In order to meet high-precision requirements, we believe, it is necessary for us to adopt these equations in the future astronomical practice.

Session 2 Reference timescale requirements (Richard N. Manchester and Gerard Petit, Chairs)

2.01. A pulsar-based timescale

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Invited

I will demonstrate how pulsar observations can be used to develop a pulsar-based timescale that can be compared with terrestrial timescales. Using observations from the Parkes Pulsar Timing Array project, I will show that we can identify known issues with TAI and have a marginally significant detection of a discrepancy between our pulsar based timescale and BIPM2011.

2.02 Long term stability of atomic time scales

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Invited

International Atomic Time TAI gets its stability from some 400 atomic clocks worldwide that generate the free atomic scale EAL and its accuracy from a small number of primary frequency standards (PFS) which frequency measurements are used to steer the EAL frequency. Because TAI is computed in "real-time" (every month) and has operational constraints, it is not optimal and the BIPM computes in deferred time another time scale TT(BIPM), which is based on a weighted average of the evaluations of TAI frequency by the PFS. We show that a point has been reached where the stability of atomic time scales, the accuracy of primary frequency standards, and the capabilities of frequency transfer are approximately at a similar level, in the low 10-16 in relative frequency. The goal is now to reach and surpass 1x10-16 and the three fields are in various stages of advancement towards this aim. We review the stability and accuracy recently achieved by frequency standards, focusing on primary frequency standards on one hand, and on new secondary realizations e.g. based on optical transitions on the other hand. We study how these performances can translate to the performance of atomic time scales, and the possible implications of the availability of new high-accuracy frequency standards operating on a regular basis. Finally we show how time transfer is trying to keep up with the progresses of frequency standards. Time transfer is presently the limiting factor at short averaging time (e.g. 1-2 weeks) but it should not be limiting the long term stability of atomic time scales, which is the main need of many applications in astronomy.

2.03. Perspectives for time and frequency transfer

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The realisation and distribution of timescales is dependent on long-distance comparisons between clocks, which are mainly carried out today using navigation and telecommunications satellite systems. The planned evolutions of current GNSS systems and the arrival of new constellations will bring possibilities for improving these comparisons, while also underlining the need for progress on the long-standing problem of the characterisation of the electrical delays of GNSS receivers and antennas. In parallel, other comparison methods are also being improved or developed, such as the use of the carrier phase in telecommunications-based methods, or the exchange of optical signals in free space or via optical fibres. We will give a brief overview of these diverse perspectives and highlight some recent developments.

2.04. Developments of optical clocks and their comparisons for future time reference

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Rapid developments of optical frequency standards have been so remarkable and it has been shown that the optical frequency standards have potential capabilities to improve the time reference. To realize the improved time reference, however, it is quite important to evaluate the accuracy and stability of the optical frequency standards and compare them located at different places. At National Institute of Information and Communications Technology (NICT), we have lately developed an optical lattice clock using 87 Sr atoms and a single-ion optical frequency standard using a 40Ca+ ion. Besides the comparisons and evaluations of the two optical frequency standards inside the institute, they have been compared with the Sr optical lattice clock at the University of Tokyo (UT) by using a fiber link. It is also planned to compare with optical frequency standards in foreign institutes by using Global Positioning System receivers. The results of such recent activities will be presented.

2.05. Connecting kinematic and dynamic reference frames by D-VLBI

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In geodetic and astrometric practice, terrestrial station coordinates are usually provided in the kinematic International Terrestrial Reference Frame (ITRF) and radio source coordinates in the International Celestial Reference Frame (ICRF), whereas measurements of space probes such as satellites and spacecrafts, or planetary ephemerides rest upon dynamical theories. To avoid inconsistencies and errors during measurement and calculation procedures, exact frame ties between quasi-inertial, kinematic and dynamic reference frames have to be secured. While the Earth Orientation Parameters (EOP), e.g. measured by VLBI, link the ITRF to the ICRF, the ties with the dynamic frames can be established with the differential Very Long Baseline Interferometry (D-VLBI) method. By observing space probes alternately to radio sources, the relative position of the targets to each other on the sky can be determined with high accuracy. While D-VLBI is a common technique in astrophysics (source imaging) and deep space navigation, just recently there have been several efforts to use it for geodetic purposes. We present investigations concerning possible VLBI observations to satellites. This includes the potential usage of available GNNS satellites as well as specifically designed missions, as e.g. the GRASP mission proposed by JPL/NASA and an international consortium, where the aspect of co-location in space of various techniques (VLBI, SLR, GNSS, DORIS) is the main focus.

2.06. Link of reference frames by pulsar observations

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Pulsar VLBI coordinates when combining with the timing coordinates based on the analysis of time of arrivals of pulsar pulses allow to link the extragalactic and dynamical reference frames. Calculation of the rotational angles is based on different pulsar timing and VLBI observations including Japanese-Russian pulsar VLBI experiments.

2.07. A Convention for Coordinated Universal Time

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To keep the calendar year synchronized with the astronomical year, intercalary days are inserted following a commonly adopted convention that defines the Gregorian Calendar. Similarly, to keep the day composed of 86, 400 Système International (SI) seconds

synchronized with the day defined by the Earth's rotation, intercalary seconds are occasionally inserted in Coordinated Universal Time (UTC). Both procedures are timekeeping adjustments that attempt to account for the fact that the astronomical phenomena cannot be characterized conveniently by an integral number of smaller units of uniform duration. In the former case the duration of the year varies slowly and predictably so that it is relatively easy to account for the length of the year and to plan ahead accordingly. In the latter case, however, the relatively unpredictable nature of the Earth's rotational speed makes the intercalation of seconds in common timekeeping difficult to predict and problematic to plan in advance. Adopting a convention analogous to the conventional rules that define the Gregorian calendar would appear to be a possible solution. The current definition of UTC requires that UT1-UTC remain less than 0.9s. Using historical data that characterize the Earth's variable rotation the magnitude of the expected values of UT1-UTC that might be expected as the result of using forecasts is evaluated for various possible conventional intercalary second models.

Session 3 Topics in Celestial Mechanics (Zoran Knezevic, Chair)

3.01. Requirements on space-time reference systems for the BepiColombo and Juno missions

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Invited

BepiColombo (BC) is an ESA mission, including two satellites orbiting Mercury, to be launched in 2015. JUNO is a NASA mission, already launched and on the way to Jupiter. Both S/C carry dedicated Ka-band transponders and other equipment to perform the most advanced interplanetary radio science experiments made possible by state of the art technology. A consistent set of models compatible with the accuracy of the range and range-rate measurements needs to include the dynamic model, the observation model, and the appropriate spacetime reference and coordinate systems. For BC the model for mercury-centric orbit has a limited need for relativistic terms, but the independent variable of the equations of motion needs to be a form of Dynamical Mercury Time, with comparatively large nonlinear differences with respect to the corresponding time coordinate with respect to the solar system barycenter (SSB). The dynamical model for the orbits of the planets Mercury and Earth need a complete PPN formulation and a large set of asteroids considered as perturbing masses; the very precise definition of the SSB is a challenge. The observation model requires as many as four separate iterations, plus a Shapiro term with second order corrections. For JUNO the dynamic model of the jovicentric orbit requires direct and tidal perturbations from many satellites, and Jupiter relativistic terms including Lens-Thirring effect; the independent variable must be a Dynamical Jupiter Time. The observations model needs to include a Jupiter Shapiro effect, including an oblateness term.

3.02. The trajectory monitoring of spacecraft via VLBI in China's lunar exploration project

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We report the current status of the Chinese VLBI network (CVN), the results of satellite tracking experiments in the past few years as related to the real-time processing of dataflow, the reliability and precision of the CVN measurements, especially, the real-time monitoring of the trajectory evolution of the Chang' E-1 and Chang'E-2 satellites by positioning reduction of tracking data. We also prospect the application of VLBI technique to the planned Chang'E-3 lunar project and to the precise tie among the radio, dynamical and lunar fixed reference frames.

3.03. General-relativistic equations of two extended bodies in the post-Newtonian approximation

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Within the framework of Einstein Theory of Gravitation we study the two-body problem and derive the equations of motion in the weak-field, slow-motion approximation. Relativistic definitions of momentum, angular momentum and center of mass in terms of multipole moments, are applied to obtain the laws of motion and the post-Newtonian approximation method is widely used in order to establish the metric to compute the equations and analyze its main characteristics.

3.04. Advanced dynamical models for very well observed asteroids: perturbations from small bodies, relativity, non-gravitational effects.

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Invited

The availability of radar data and high precision optical observations has increased the number of objects with a very well constrained orbit, especially for those objects with a long observed arc. In these cases, the uncertainty of orbital predictions is often dominated by the inaccuracy of the dynamical model. However, the motion of small solar system bodies poses a serious challenge in modeling their dynamics. In particular, for those objects with a chaotic motion small differences in the model are amplified with propagation. Thus, we need to take into account small perturbations too, especially for long-term prediction. An improved dynamical model is relevant in several applications such as assessing the risk of an impact between an asteroid and the Earth. The N-body model describing the motion of a small solar system body includes the Newtonian attraction of the planets. The contribution of other perturbing bodies has to be taken into account. We propose to include the Moon, two dwarf planets (Ceres and Pluto) and fifteen asteroids (Pallas, Vesta, Juno, Metis, Hygiea, Eunomia, Psyche, Amphitrite, Euphrosyne, Europa, Cybele, Sylvia, Davida, Herculina, Interamnia). The next step is the introduction of the relativity terms due to both the Sun and the planets. Despite their small magnitude, planetary relativistic terms turn out to be relevant for objects experiencing close approaches with a planet. Finally, we discuss non-gravitational effects such as solar radiation pressure and the Yarkovsky effect. In particular, the latter acts as a tiny but secular semimajor axis drift that may decisively drive long-term predictions. These non-gravitational effects are difficult to model as they depend on object' s physical properties that are typically unknown. However, a very well observed object can have an orbit precise enough to allow the determination of the parameters defining a non-gravitational perturbation and thus the modeling of the corresponding acceleration.

3.05. Phoebe's orbit from ground-based and space-based observations

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Phoebe is the ninth satellite of Saturn and presents a retrograde orbit. The orbit of Phoebe is not so accurate for three main reasons. The dynamical models are sometimes too basic (taking into account only perturbations of planets), the astrometry is not homogeneous and the Phoebe's position is dependant to Saturn's theory (planetary ephemerides). Consequently, we have developed a new dynamical model by taking into account the perturbations of the main planets and of the Saturnian satellites (using the most recent theories) and the Saturn's flatness. In order to fit the dynamical model, we have compiled more than 3000 observations from 1898 to 2011 including ground-based observations and space-based observations from Voyager and Cassini. Some observations in the early XXth century have been reduced with accurate stellar catalogue and most of ground-based observations have been treated from bias of stellar catalogues. Finally, we present an accurate orbit of Phoebe and a comparison with the previous theories.

3.06. The geoid computed from a new generalized theory of the figure of the Earth

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The geoid serves as the reference frame in geodesy. The Clairaut equation, Darwin-de Sitter theory and the series work of Denis are regarded as the standard theories of equilibrium figures of the Earth to the first-, second-, and third-order precision, respectively. Recently, a new generalized theory to obtain the interior figures to third-order accuracy was developed (Liu & Huang, 2008; Huang & Liu, 2012), in which, both the direct and indirect contribution of the anti-symmetric crust layer are included, thus, all the non-zero order and odd degree terms, up to degree/order of six, are included in the spherical harmonic expression of the equilibrium figures. As a result, the global dynamical flattening (H) was obtained as 1/306.68, i.e., the difference of H between the calculated value from above traditional theories and the value from precession observations is reduced from 1.1%, by about 2/3, to 0.38%. In this presentation, based on the above new generalized theory, the geoid is calculated and compared with the one derived from EGM96. Some further discussion will be also presented.

3.07. May Small Digital PZT And Radio Beacons Improve The LPhL For Future Lunar Missions?

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LLR is the current unique precise method to measure the LPhL since the Apollo missions. After 40years observations, the measuring error of LPhL amplitudes have been reduced to about a couple of tens milli-arcseconds. To improve the measuring precision of LPhL, the new ideas of digital PZT (ILOM) and radio beacons are suggested by researchers from Japan, Russia and China for up-coming lunar missions. To promote above ideas in these missions, we developed a prototype PZT, proposed radio beacons on CE-3/4 lunar landing missions and on Lunar-Glob/Resource lunar landing missions. We are also developing the small VLBI antennas in Russia and China to prepare the possible LPhL joint in-beam radio observation from later 2013 or earlier 2014. The analyzing work of simulations have been carried out. Additionally, the newly developed digital PZT technique will also be used on measuring the

local or regional plume line variation, which has been recently noticed closely related to the volcano and earthquake activities on the Earth (See Li et al. and Yang et al. in this meeting

3.08. Progress of astrometric research in Nikolaev Observatory

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A catalog of astrometric positions and proper motions of 140237 stars in fields of ecliptical zone and high proper motion stars was derived from CCD-observations made at AMC telescope (Nikolaev) in 2008-2009. The UCAC2 catalog was used as a reference one for astrometric reductions. The standard error for a single position is 20-65 mas in right ascension and 30-70 mas in declination. Cross–identification of the obtained data with modern astrometric catalogs such as TYCHO2, 2MASS, CMC14, PPMX, XPM, USNO-A2.0 and XPM-1.0 was made for investigation systematical errors and calculation of the proper motions [1]. The final catalog contains star positions, proper motions as well as photometric data (B, V, r´, J, H, K) taken from other catalogs. For analysis of perturbed motion of selected asteroids, there was made astrometric reduction for three thousands of positions of 68 selected asteroids observed at the Russian-Turkish telescope RTT150 in 2008-2011 [2]. The research is conducted within the International Joint Project between IMCCE (France), NAO (Ukraine), KFU (Russia), and TUG (Turkey). The reduction was made with the UCAC2 and UCAC3 catalogs. The standard error of a single position is 0.15 arcsec in right ascension and 0.13 arcsec in declination. Also, the first results of astrometric reduction are presented for the observations of selected asteroids made at the AZT8 (Evpatoriya) and Mobitel (Nikolaev) telescopes. The obtained positions are expected to be used for derivation masses of asteroids by dynamical method. This work is supported by State Agency on Science, Innovation and Information of Ukraine, Russian Foundation for Basic Research. 1. Jin, W., Pinigin, G., Tang, Zh., Shulga, A. (2011). The collaboration between ShAO and NAO: Celebration of the 190th anniversary of NAO. Proc. Int. Conf. "Astronomical Research: from near-Earth Space to the Galaxy", Nikolaev (pp. 92-104). 2. Ivantsov, A., Gumerov, R., Khamitov, I., Aslan, Z., Thuillot, W., Pinigin, G., Hestroffer, D., Mouret, S. (2011). Analysis of Astrometry and Photometry Observations of Asteroids at the RTT150. Proc. Workshop "Gaia Follow-up Network for Solar System Objects", Paris (pp. 93-96).

Session 4 Space mission requirements (Nicole Capitaine, and Dafydd Wyn Evans, chairs)

4.01. Time and frequency transfer with the ESA/CNES ACES-PHARAO mission

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Philippe Laurent, SYRTE/Paris Obs./CNRS/UPMC
Invited

The Atomic Clocks Ensemble in Space (ACES-PHARAO mission, which will be installed on board the International Space Station (ISS) in 2014, will realize in space a time scale of very high stability and accuracy. This time scale will be compared to a ground clock network thanks to a dedicated two-way microwave link. The ACES mission will demonstrate the capability to perform phase/frequency comparison between space and ground clocks with a resolution at the level of 0.4 ps over one ISS pass (300 s), 8 ps after 1 day, and 25 ps after 10 days of integration time. For that purpose our team is developing advanced time and frequency transfer algorithms. The altitude difference between the ACES-PHARAO clock and ground clocks will allow measuring the gravitational red shift with unprecedented accuracy, as well as looking for a violation of Lorentz local invariance. Several ground clocks based on different atomic transitions will be compared to look for a drift of the fine structure constant. Moreover, the mission will pave the way to a new type of geodetic measurement: the gravitational red shift will be used to measure gravitational potential

4.02. Celestial Reference Frame Realizations at Multiple Radio Frequency Bands

Chris Jacobs, christopher.s.jacobs@jpl.nasa.gov, Jet Propulsion Laboratory
Invited

The International Celestial Reference Frame (ICRF) was adopted by the IAU in 1997 based on VLBI measurements at S/X-band (2.3/8.4 GHz) and complemented by HIPPARCOS measurements at optical frequencies. At that time, the IAU encouraged the astrometric community to extend the ICRF to additional frequency bands. In response, VLBI measurements have been made at 24, 32, and 43 GHz. Meanwhile, the 8.4 GHz work has been greatly improved with the release of the ICRF-2 in 2009. This paper will discuss the programmatic and scientific motivations for extending the ICRF to these higher radio bands. Results to date will be summarized including evidence that these new high frequency frames are rapidly approaching the accuracy of the 8.4 GHz ICRF-2. We will discuss the current limiting errors and prospects for the future accuracy of radio reference frames. In particular, we will discuss using multiple radio frames to characterize the frequency dependent systematic noise floor from extended source morphology and core shift. Finally, given the potential of the Gaia optical mission for state-of-the-art astrometry, we will discuss simulations

which show the potential for a radio-optical frame tie at the 10-15 µas level of precision (1-sigma). The research described in this paper was done under contract with NASA. Government sponsorship acknowledged. ©2012 California Institute of Technology.

4.03. Status of Gaia and early operation plans

Francois Mignard, francois.mignard@oca.eu, Observatoire de la Côte d'Azur
Invited

The ESA space astrometry mission is scheduled for a launch in the second half of 2013. I will summarize the overall science goals, focusing on the astrometric aspect, and present the expected performances in this area, including the contribution to the realisation of an optical reference frame. One year before launch, I will also describe the early operations for the data processing and the current plans for the science releases.

4.04. Current status of the celestial reference frame and future prospects.

Ralph Gaume, U.S. Naval Observatory

We will review the current status of the Celestial Reference Frame at optical, infrared, and radio wavelengths. The USNO has recently released the UCAC4 star catalog and begun the northern hemisphere observation phase of the URAT program at the Naval Observatory Flagstaff Station located in Flagstaff AZ . USNO is currently working to produce astrometric star catalogs from large A-Omega programs such as Pan-STARRS. The current status of the JMAPS bright-star space astrometry mission will be discussed. Improvements in the International Celestial Reference Frame, ICRF2, may be realized through various means, including higher frequency radio-wavelength observations, where source structure is less pronounced. A proposal to lead to a future higher accuracy radio reference frame will be discussed.

4.05. Next-generation VLBI model: higher accuracy and larger baselines

Sergei Klioner, sergei.klioner@tu-dresden.de, Lohrmann Observatory, Technische Universität Dresden

Twenty years after the formulation of the consensus VLBI model as appear in the IERS conventions, we have now the necessity to improve both the accuracy of the model and, anticipating various space-science applications, to increase the maximal allowed length of the baseline. This presentation overviews the improved model that gives an accuracy of 0.1 ps for Earth-bound baselines valid for VLBI observations of spacecrafts as well as suitable for space-based VLBI.

4.06. New Pulkovo combined catalogues of the radio source positions.

Yulia Sokolova, julia.rs07@hotmail.com, Pulkovo Observatory
Zinovy Malkin, malkin@gao.spb.ru, Pulkovo Observatory

Catalogues of radio source positions (RSC) obtained from Very Long Baseline Interferometry (VLBI) observations serve as the realizations of the IAU International Celestial Reference System (ICRS) since 1998. With increasing of the volume and improving the accuracy of VLBI observations with time, development of advanced methods of the RSC construction is a topical problem to realize the full potential of VLBI technology. This task becomes more and more important nowadays in view of expected during coming years realization of the VLBI2010 network and highly accurate GAIA catalogue of optical positions of extragalactic objects. One of the commonly used methods of improving the accuracy of the source position catalogues is construction of a combined catalogue. In this paper, we present new Pulkovo combined catalogues PUL(2012)C01 and PUL(2012)C02 which have been constructed mainly following the strategy developed by Sokolova & Malkin (2007, A&A, 474, 665). Besides using more data, several developments were realized such as improved method of determination of the optimal number of the expansion terms, more careful investigation of the stochastic errors of input catalogues, improved weighting scheme, additional test of the quality of the individuals and combined RSC, etc. The PUL(2012)C01 catalogue is aimed at stochastic improvement of the ICRF2, the PUL(2012)C02 catalogue is constructed in the independent system. Results of comparison of our combined catalogues with individual catalogues and ICRF2 are presented.

4.07. Morphology of QSOs - the gridpoints of the Gaia Celestial Reference Frame

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The acronym QSO refers to the particular time in the life of giant galaxies, often elliptic ones, when the nucleus becomes extremely active fueled by matter infalling onto the accretion disk feeding the massive central black hole. But the duration and intensity of such a phase make QSOs to be treated as a class of objects, and indeed a class of enhanced cosmologic, astrophysical and astrometric bearings. As a consequence, even in the optical domain, the morphology of a quasar can be understood as comprehending the domineering central source, the immediate surrounding regions, the jet basis and features along the jet, and a bright host galaxy which is likely to be intensely star forming and generally speaking a lively place in itself. Morphology, and its color dependent aspects, can thus inform on the physical processes at work on a given QSO, for example what is likeness to exhibit different time scales of variability. The ESA Gaia mission will have its fundamental reference frame formed by quasars, which are desired to be as point like as can be gathered for the sake of ensuring maximum astrometric precision and accuracy. We will present how the morphology characteristic is indicated in the Gaia Initial QSO Catalog and the related investigations. We will also outline the Gaia extended sources methods that will be applied to all QSOs observed, and the vast amount of information that will be made available from the mission outcomes.

4.08. Systematic effect of the Galactic aberration on the ICRS realization and the Earth orientation parameters

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The curvature of the motion of the solar system barycenter (SSB) around the Galactic center induces an aberration effect varying linearly with time that can be called "Galactic aberration". This results in a systematic dipole pattern of the apparent proper motions of the ensemble of distant extragalactic objects which defines the International Celestial Reference System (ICRS). The purpose of this paper is to investigate the effect of the Galactic aberration on the ICRS realization and on the Earth orientation parameters (EOP) referred to the ICRS. We first compute theoretically the global rotation of the ICRS resulting from the Galactic aberration effect and then evaluate the corresponding influence on the EOP using CIO based ICRS-to-ITRS coordinate transformation. Based on the ICRF and ICRF2 catalogs, we evaluate this effect over short and long time intervals. We have demonstrated that the effects of the Galactic aberration strongly depend on the distribution of the sources that are used to realize the celestial reference system. According to the realistic distribution of the defining sources of the ICRF and ICRF2, the amplitudes of the systematic effect on the coordinates of the Celestial intermediate pole (CIP) are up to 50 and 5 microarcseconds, respectively after one century from J2000.0 while the effects on the Earth Rotation Angle (ERA) are of several tens of microarcseconds. The Galactic aberration effect cannot be neglected with the improving precision in modern astrometry and the increasing length of the available VLBI observation time series. More radio sources, especially in the southern hemisphere should be observed to make more homogeneous distribution of the defining sources in the ICRF in order to minimize that effect.

4.09. Dipole systematic effect in proper motion of the reference radio sources

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We report new estimates of the dipole systematics in the proper motion of the reference radio sources, based on VLBI observations over the period 1990-2012. Geodetic and astrometric VLBI data were processed using the CALC/SOLVE software package to calculate individual time series of the equatorial coordinates. Additionally, we analysed impact of the criteria for outlier rejection on the dipole component estimates.

4.10. Towards ICRF3: preparing the VLBI frame for future synergy with the Gaia frame

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The European space astrometric mission Gaia to be launched in 2013 will produce a QSO-based celestial reference frame with unprecedented position accuracy and sky density. By the end of the decade, two highly-accurate reference frames will thus cohabit, the International Celestial Reference Frame (ICRF) derived from Very Long Baseline Interferometry (VLBI) data and the Gaia optical frame, both with individual source position accuracies below 100 microarcseconds. For consistency between optical and radio positions, it will be fundamental to align the two frames with the highest possible accuracy. This is important not only for continuity of celestial frames but also to exploit at best their synergies for astrophysics. The latter includes probing the Active Galactic Nuclei (AGN) jets properties and the physics of these objects by comparing the spatial location of the optical and radio emission regions. The alignment between the VLBI and Gaia frames requires a large number of sources common to the two frames, i.e. radio-loud QSOs with position accurately known from both VLBI and Gaia. This implies that the sources must be brighter than magnitude 18 (so that their Gaia positions may be derived with the highest accuracy) and have compact VLBI structure on milliarcsecond scales (for highly-accurate VLBI positions). In this paper, we review the current source potential for this alignment based on the ICRF2 and an ongoing dedicated VLBI project aimed at finding additional weaker extragalactic radio sources for this purpose. We also stress that these sources must be monitored during the mission (especially their VLBI position stability and structure) in order to control

their relevance for the alignment, and present the observations we envision to this end in the framework of the IVS and other VLBI networks.

Session 5 Future requirements for planetary ephemerides (George Kaplan, Chair)

5.01. INPOP: evolution, applications and perspectives

Jacques Laskar, laskar@imcce.fr, IMCCE, Observatoire de Paris
Agnes Fienga, Obs. Besançon
Hervé Manche, IMCCE, Observatoire de Paris
Ashok Verma, Obs. Besançon
Mickael Gastineau, IMCCE, Observatoire de Paris
Invited

The INPOP ephemerides have known several improvement since the last INPOP10a release (Fienga et al. 2011a) . Improvement in the asteroid masse determinations have been implemented in using a priori sigmas and bound values least squares. Estimations of 120 asteroid masses have then been obtained with INPOP10b and presented in (Fienga et al. 2012a). TDB and TCB versions of this ephemerides have been distributed through the INPOP website as well as spice format versions. Studies about solar corona have also been investigated leading to new electron density modeling presented in (Verma et al. 2012b). Adjustments of the Moon libration and orbits are also continuously operated. Perspectives will also be drawn during this talk, especially related to the analysis of spacecraft data (Messenger) for the planetary orbits and to the combination of spacecraft and LLR data for the Moon orbit and libration. A. Fienga, J. Laskar, P. Kuchynka, H. Manche, G. Desvignes, M. Gastineau, I. Cognard, and G. Theureau, 2011a, “The INPOP10a planetary ephemeris and its applications in fundamental physics,” Celestial Mechanics and Dynamical Astronomy, vol. 111, pp. 363–385. A. Fienga, P. Kuchynka, J. Laskar, H. Manche, and M. Gastineau, 2012a “Asteroid mass determinations with INPOP planetary ephemerides,” in EPSC-DPS Joint Meeting 2011, p. 1879. A. K. Verma and A. Fienga, 2012b “Re-Estimation of Solar Corona Coefficients (a, B, c) by Using MGS Mex Spacecraft Datas,” in EPSC-DPS Joint Meeting 2011, p. 1828.

5.02. Linking the Planetary Ephemerides to the ICRF

William Folkner, william.folkner@jpl.nasa.gov, JPL
Petr Kuchynka, jaapetr@gmail.com, Jet Propulsion Laboratory, California Institute of Technology
Invited

An extensive campaign of very long baseline interferometry (VLBI) and range measurements of spacecraft in orbit about Mars have been performed by the NASA Deep Space Network since 1999 in order to support increasingly stringent targeting for spacecraft landings at Mars. The measurement campaign has intensified in the last few years leading up to the Mars Science Laboratory (MSL) landing on Mars in August 2012. MSL requires that the orbit of Mars with respect to Earth be determined with an accuracy better than 300 meters. As a result of the measurement campaign, the orientation of the orbits of the Earth and Mars with respect to the International Celestial Reference Frame (ICRF) has been determined with an accuracy of 0.1 milli-arcseconds. The distances from the Earth to the Sun are estimated to have uncertainties of a few meters for several centuries about the current epoch. The improved ephemeris of the Earth provides an accurate reference for pulsar timing experiments. The accuracies of the orbits of Mercury, Venus, and Saturn have been recently improved from measurements of the MESSENGER, Venus Express, and Cassini spacecraft respectively. The current planetary observation sets and residuals to fitted ephemerides will be described. The next major improvement in the planetary ephemerides is expected to come with the arrival of the Juno mission at Jupiter in 2016.

5.03. EPM – the high-precision planetary ephemerides of IAA RAS for scientific research, astronavigation on the Earth and space

Elena Pitjeva, evpitjeva@gmail.com, Institute of Applied Astronomy RAS
Invited

For constructing planetary ephemerides adequate modern observations it is necessary to take into account all influencing factors. A dynamical model of EPM ephemerides originating in the seventies of the last century includes mutual perturbations from the major planets, the Sun, the Moon and 5 more massive asteroids, perturbations from the other large 296 asteroids and the 21 largest trans-Neptunian objects, perturbation from the massive asteroid ring with the constant mass distribution and perturbation from the massive ring of TNO in the ecliptic plane with the radius of 43 au, as well as perturbations due to the solar oblateness. The EPM ephemerides have been constructed by numerical integration of the equations of motion of bodies taken in the post-Newtonian approximation in the Schwarzschild field in the BCRS coordinate system for the TDB time scale. The EPM2012 ephemerides have been fitted to about 680000 observations of different types from classical meridian to modern planet and spacecraft ranging 1913-2010. Millisecond pulsars may be used for estimation of linking between dynamical planetary frame and the ICRF, however this tie is realized more accurate by including into the total ephemeris solution the ICRF-base VLBI measurements of spacecraft near planets. The rotation angles for the orientation of EPM2012 onto ICRF have been determined with the accuracy better than 0.1 mas from 213 VLBI observations of spacecraft (Magellan, Phobos, MGS, Odyssey, Venus Express, etc.) 1989 – 2010 in mas: ex= 0.002±0.042, ey=0.000±0.048, ez=0.001±0.028. Distances and radial velocities for planets are estimated quit accurately for planets provided by ranging, however uncertainties of their positions depend on uncertainty of the orientation their orbits. The present maximum errors of the Earth orbit determined from comparison of heliocentric X, Y, Z coordinates, velocities, and distances for DE423 and EPM2012 are 382 m (coordinates), 0.08 mm/sec (velocities), 7.3 m (distances) on the 1950-2050 time interval. At present EPM ephemerides are the basis for the Russian Astronomical Yearbook, used in the navigation program “GLONASS” and different investigation: determination of physical parameters (masses asteroids, parameters of planet rotation and topography, the solar oblateness (1.98±0.19)•10E-7, GM_Sun and its time variation), the relativistic parameters (beta-1)=(2.8±3.2)•10E-5, (gamma-1)=(-5.2±6.1)•10E-5, $\dot{G}/G$), and corrections to the planet perihelion advances, from them the upper limit on mass of dark matter in the Solar System has been obtained.

5.04. A new approach to asteroid modeling in a planetary ephemeris

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Tracking of Mars orbiting spacecraft currently provides a measurement of the Earth-Mars distance with an accuracy of about 1 m. These accurate observations have been carried out almost without interruption since 1999 and can be expected to continue in the future. The accuracy and the growing amount of range data present a considerable challenge in terms of the implementation of asteroid perturbations in a planetary ephemeris. On the one hand, it is necessary to select relevant asteroids to include in the dynamical model. On the other hand, the masses of the selected asteroids need to be correctly adjusted to the range observations. The standard approach to this twofold problem consists in selecting about 300 asteroids for the dynamical model. The selection is based on the amplitudes of the individual perturbations induced on the Earth-Mars distance. The mass of each selected asteroid is then estimated by separating the asteroids into major and minor objects. Asteroids in the first category have their masses adjusted individually. Asteroids in the second category have their masses determined from radiometric diameters and three adjusted density parameters (one for each taxonomic class C/S/M). The disadvantage of this standard approach, or any of its variations, is the difficulty in controlling the systematic errors introduced by the asteroid selection and by the splitting into minor and major categories. As the number of observations grows, systematic errors occasionally become apparent in the adjusted masses. The asteroid selection and category splitting needs then to be adapted to better suit the new observational data set. In this contribution, I suggest a new approach to asteroid mass estimation. The approach relies on Tikhonov regularization where prior constraints on asteroid masses are determined from WISE radiometric diameters. Various authors have used prior constraints to estimate asteroid masses. With respect to these previous efforts, the new approach has the notable advantage of providing a simple and rigorous framework to control systematic and random errors. It is then possible to construct an asteroid model, which can be adjusted, without any modifications, to current and future range observations. In the new approach, the obtained estimates of asteroid masses are robust in terms of the model selection. We avoid any sophisticated search for the "optimal" selection of asteroids to include in the dynamical model. Also, there is no need to split asteroids into minor and major categories, because all asteroid masses are considered individually. The process of selection and parameter estimation is thus greatly simplified. The new approach is used to fit the asteroid model of the JPL planetary ephemeris to recent Mars ranging data. About 30 asteroid masses are determined to better than 35%. The masses agree well with determinations obtained by other methods, based for example on the observations of close encounters between asteroids. The adjusted ephemeris also exhibits good behavior in terms of the Earth-Mars range extrapolation.

5.05. New developments in spacecraft raw data direct analysis for the INPOP planetary ephemerides

Ashok Verma, ashok@obs-besancon.fr, Observatoire de Besançon
Agnes Fienga, Observatoire de Besançon

In this talk, we will describe the requirement that planetary ephemerides be fitted to normal points derived from spacecraft raw data analyzed with consistent software. Some examples will be given of the impact of software inconsistencies on the INPOP construction and applications. A short introduction to the currently developed ODS software for spacecraft data analysis will be given, as well first results.

5.06. The re-definition of the astronomical unit of length: reasons and consequences

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Sergei Klioner, sergei.klioner@tu-dresden.de, Lorhmann observatory, TU Dresden, Germany
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The astronomical unit (au) is a unit of length approximating the Sun-Earth distance that is used mainly to express the scale of the solar system. Its current definition is based on the value of the Gaussian gravitational constant, k. This conveniently provided accurate relative distances (expressed in astronomical units) when absolute distances could not be estimated with high accuracy. The huge improvement achieved in solar system ephemerides during the last decade provides an opportunity to re-consider the definition and status of the au. This issue was discussed recently by Klioner (2008), Capitaine & Guinot (2009) and Capitaine et al. (2011), as well as within the IAU Working Group on "Numerical Standards for Fundamental astronomy". This resulted in a proposed IAU Resolution recommending that the astronomical unit be re-defined as a fixed number of Système International d’ Unités (SI) metres through a defining constant. For continuity that constant should be the value of the current best estimate in metres as adopted by IAU 2009 Resolution B2 (i.e. 149 597 870 700 m). After reviewing the properties of the IAU 1976 astronomical unit and its status in the IAU 2009 System of Astronomical Constants, we explain the main reasons for a change; we present and discuss the proposed new definition as well as the advantages over the historical definition. One important consequence is that the heliocentric gravitational constant, GM(Sun), would cease to have a fixed value in astronomical units and will have to be determined experimentally. This would be compliant with modern dynamics of the solar system as it would allow

Session 6 Relating reference systems (Harald Schuh, Chair)

6.01. Connecting terrestrial to celestial reference frames

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Invited

Terrestrial and celestial reference frames (TRF and CRF) and the Earth Orientation parameters (EOP) realizing the tie between TRF and CRF are key products of geodesy and astrometry. They are derived from processing of data obtained with several, primarily space geodesy, techniques. Only Very Long Baseline Interferometry (VLBI) technique provides a consistent computation of CRF, TRF and EOP in a single global solution. VLBI is also the only technique for determination of the celestial pole movement and the basic technique to determine the Universal Time. However it has serious deficiencies such as non-continuous observations and relatively small number of active stations with rather uneven distribution over the globe. On the other hand, satellite techniques provide accurate and dense Polar motion and length of day series, as well as TRF realizations. But they do not provide a direct link to the celestial reference system as does VLBI, and cannot determine all types of EOP, although are useful for the Universal Time and celestial pole offset densification. Therefore, a combination of the results obtained with different techniques is the only way to achieve a highly accurate, dense and consistent TRF-CRF-EOP solution. Unfortunately, all the techniques have own stochastic and systematic errors. Besides, the satellite data processing involves supplement groups of parameters such as space targets' orbits and geopotential coefficients which may additionally disturb a final solution. For these reasons, the multi-technique combination is not a simple task. It becomes more and more complicated as the requirements to all the components of this triad grow steadily, and a mm/muas level of accuracy is the current goal. In this presentation, we give an overview of methods of computations of consistent TRF-CRF-EOP solutions, as well as existing problems and prospects.

6.02. SOFA, an IAU service for the future

Catherine Hohenkerk, catherine.hohenkerk@ukho.gov.uk, HM Nautical Almanac Office/UKHO
Invited

Standards of Fundamental Astronomy (SOFA) is an International Astronomical Union (IAU) service that provides accessible and authoritative algorithms and procedures that implement standard models used in fundamental astronomy. SOFA consists of a dedicated web site from which the SOFA Software Collections (Fortran and ANSI C) may be downloaded and a Board that provides and checks the material. This talk highlights SOFA's development, what it provides users and the IAU, as well as indicating issues that may arise in the future.

6.03. The IERS Conventions (2010): Reference Systems and New Models

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Gérard Petit, Bureau International des Poids et Mesures
Invited

The IERS Conventions (2010) provides the international standard for models to be used in the generation of celestial reference systems (CRS), terrestrial reference systems (TRS), and the Earth orientation parameters (EOPs) that relate the associated reference frames. The models in the new Conventions provide significant improvements when compared to the models of the previous IERS Conventions (2003). This presentation will provide an overview of the latest adopted models and standards, which include: numerical standards, reference systems, transformations between systems, geopotential, displacement of reference points, tidal variations, atmospheric propagation delays, and relativistic models. This presentation will also compare the current models to the previous models and provide quantitative estimates of the improvement. Finally, the presentation will conclude by providing future plans for the Conventions.

6.04. Link the EOC4 catalog to the ICRS.

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One of the method, used to link Hipparcos reference frame to the International Celestial Reference System (ICRS) Kovalevsky et al. 1997, A&A 323), was an indirect method using Celestial Pole Offsets (CPO) derived from optical astrometry observations in period 1900-1992 (Vondrak et al. 1997, A&A 319). The last solution of Earth Orientation Parameters (EOP) including CPO from the Optical Astrometry observations in the period 1900-1992 was published recently (Vondrak et al. 2010). The solution is done in the

reference system of the catalog EOC4 Vondrak, Stefka, 2010, A&A 509). The CPO show statistically significant linear trends (dX=29mas/cy, dY=9mas/cy) although the latest precession/nutation model IAU2000/ was used for the reduction of observations. The trends are of the same order (+-0.25mas/yr) as the standard error of the spin of Hipparcos reference frame declared in Kovalevsky et al. (1997). The analysis of the trends and their possible implication to the slight rotation of the ICRS representation at the optical wavelengths will be discussed.

6.05. A new numerical theory of Earth rotation

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Nowadays the rotation of the Earth can be observed with an accuracy of about 0.01 milliarcseconds (mas), while theoretical models are able to describe this motion at a level of 1 mas. This mismatch is partly due to the enormous complexity of the involved processes, operating on different time scales and driven by a large variety of physical effects. But also partly due to the used models, which often use simplified and linearized equations to obtain the solution analytically. In this work we present our new numerical theory of the rotation of the Earth. The model underlying the theory is fully compatible with the post-Newtonian approximation of general relativity and is formulated using ordinary differential equations for the angles describing the orientation of the Earth (or its particular layers) in the GCRS. These equations are then solved numerically to describe the rotational motion with highest accuracy. Being initially developed for a rigid Earth our theory was extended towards a more realistic Earth model. In particular, we included 3 different layers (crust, fluid outer core and solid inner core) and all important coupling torques between them as well as all important effects of non-rigidity, such as elastic deformation, relative angular momenta due to atmosphere and ocean etc. In our presentation we will describe the details of our work and compare it to the currently used models of Earth rotation. Further, we discuss possible applications of our numerical theory to obtain high-accuracy models of rotational motion of other celestial bodies such as Mercury.

6.06. Asymmetric effects in polar motion excitation

Christian Bizouard, christian.bizouard@obspm.fr, Observatoire de Paris/SYRTE, France

Polar motion analysis is generally based upon symmetric linearised Euler-Liouville equations. It means that the equatorial components of the rotation pole play equivalent role. But, when triaxiality and asymmetry of the ocean pole tide are not cast aside, the geodetic excitation becomes asymmetric with respect to the pole coordinates. This leads to the formulation of generalised Euler Liouville equation, for which we derive a general solution. Then a circular equatorial excitation at a given frequency also produces circular polar motion of opposite frequency. The effect is quantified and is found to be very significant in light of the modern accuracy of the pole coordinate estimates.

6.07. Evaluation of the accuracy of the IAU 2006/2000 precession-nutation

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The purpose of this presentation is to evaluate the accuracy of the IAU 2006/2000 precession-nutation model that was adopted by IAU Resolutions in 2000 and 2006. We first review the improvements that have been proposed by various authors in the theory, the analytical developments and the physical parameters since the adoption of the model. We then compare the model with the most accurate time series of VLBI celestial pole offsets referred to different realizations of the celestial reference system (e.g. ICRF1, ICRF2). We also look at the potential of other techniques, or different types of data, for future improvements of the model. We finally review the parameters of the model that are expected to be improved and their importance for future requirements.

6.08. Impact of IERS Conventions (2010) on VLBI-derived reference frames

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The current realization (ICRF2) of the International Celestial Reference System is based on a single solution by one technique: VLBI. The VLBI data analysis involves a number of models and other analysis options. The models applied to VLBI and further space-geodetic techniques are specified through IERS Conventions, while the VLBI-specific models used for the realization of conventional celestial reference systems are defined by the International VLBI Service for Geodesy and Astrometry (IVS). IERS Conventions (2010) provide several updates including reference frames, geophysical and other models, which have to be used for the determination of international VLBI-based products. Quantifying systematic and other effects on the reference frames is a major issue for the assessment of the quality and consistency of the frames. In this context, the terrestrial reference frame is considered as well because there are interactions between the frames. The paper presents the impact of each model update on celestial and terrestrial frames given by empirically comparing two solutions; one obtained using the old and one using the new conventions. The

impact of the complete convention update can be obtained applying all changes at once. Implications following the new conventions (2010) are interpreted and commented from the VLBI-analyses' point of view.

6.09. Influence of the inner core on the rotation of the Earth revisited

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We revisit the role played by the inner core on the rotation of a three layer Earth model composed by an axial--symmetric rigid mantle, a fluid core, and an axial-symmetric rigid inner core. As it is well known, the presence of the rigid inner core introduces three additional degrees of freedom into the rotational dynamics of the system, making possible a relative, or differential, rotation between the mantle and the inner core itself. It qualitatively influences the rotation of the Earth in two different ways. One, of indirect nature, is associated with the change in the response of the Earth to the same forced perturbations as those considered for one or two layer Earth models. The other one, of direct nature, stems from the variation in the external gravitational potential of the Earth caused by the relative rotation of the inner core. Within the framework of the Hamiltonian theory of the rotation of the non-rigid Earth we derive analytical expressions for direct and indirect contributions, providing the evolution of the Earth figure axis. Those formulas allow us comparing the amplitudes arising from both effects, as well as discussing their dependence on the rheological parameters of the model.

6.10. Researches on predictions of Earth orientation parameters

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Earth orientation parameters (EOP) are essential for transformation between the celestial and terrestrial coordinate systems, which has important applications in the Earth sciences, astronomy and navigation system. In this report, we firstly describe the principles and analyze the characteristics of several commonly used EOP prediction methods. Based on this discussion, we found that it's essential to select appropriate method and length of base prediction sequence at different prediction span, e.g., autoregressive (AR) model has a higher accuracy in short-term forecasting, while the artificial neural network (ANN) model has advantage in the long term forecasting. Secondly, we employ for the first time a combination of AR model and Kalman filter (AR+Kalman) in short-term EOP prediction. Comparing with the single AR model, the combination of AR model and Kalman filter shows a significant improvement in short-term EOP prediction. At last, we will present the recent work during the period of our participation in the Earth Orientation Parameters Combination of Prediction Pilot Project (EOPC PPP). The EOPC PPP was initiated by the International Earth Rotation and Reference Systems Service (IERS) and Jet Propulsion Laboratory (JPL) in the summer of 2010, with the goal to develop a strategy for combining predictions.