Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)


PPS03-01 Room:202 Time:May 20 14:15-14:30

# LLR simulation study for future observations

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Introduction: Lunar Laser Ranging (LLR) measures the distance between laser link stations on the Earth and retroreflectors on the Moon by detecting the time of flight of photons from a high-powered laser pulse emitted from the ground stations. Since the Earth-Moon distance contains information on lunar orbit, lunar solid-body tides, and lunar orientation and rotation, we can estimate the inner structure of the Moon by constraining relevant physical parameters. Several lunar landing missions which will carry new retroreflectors to the lunar surface are under study in several countries. Furthermore, retroreflectors with a larger single aperture are under development for more precise ranging, apart from the conventional array-type retroreflectors that were realized in the Apollo and Luna mission from 1969-1973. It is not obvious how lunar physical parameters such as Love numbers will be better constrained by using range data with higher accuracy. Therefore we have conducted a simulation study of the LLR observations by using the LLR analysis software of JPL.

Method: Simulated data were created by adding noise to the predicted distances between the Earth surface and retroreflectors on the Moon using the lunar ephemeris and range model. The simulated data were fit using a least-square solution, and then the uncertainties of the fit were evaluated. There are high degrees of freedom for the creation of simulated data in terms of the number and locations of retroreflectors, the amount of data from each retroreflector, etc. In this study we set the condition as follows:

-the number of yearly range data was set to be about 600, monthly about 50
-the numbers of range data toward the new retroreflectors are at the same level as for the Apollo 11 and 14 sites
-range accuracy for new retroreflectors was set one order-of-magnitude higher than that of the existing retroreflectors
-locations of the new retroreflectors are near the north pole, near the south pole, and the mid-latitude.

Results and remarks: After about 35 years of observation, the uncertainty of some parameters is reduced by about 1/2 by adding one high-accuracy retroreflector compared to the case in which only existing retroreflectors are ranged. It is suggested that the uncertainty could be reduced by observing high-accuracy retroreflectors more than existing ones, or changing the weighting of data.

Keywords: LLR, rotation, tide, Moon, retro-reflector, simulation

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PPS03-02 Room:202 Time:May 20 14:30-14:45

# Determination of the normal modes of the Moon's libration

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The Lunar Laser Ranging experiment has been active since 1969 when Apollo astronauts placed the first retroreflector on the Moon. The data accuracy of a few centimeters, over a time-span of several decades, along with the numerically integrated ephemeris, DE421, encourages analysis of the lunar physical librations, and especially the detection of three modes of free physical librations (longitude, latitude, and wobble modes). This analysis was performed by using iteratively a frequency analysis and linear least-squares fit of the wide spectrum of DE421 Moon's physical librations. From this analysis we identified and estimated about 130 terms in the angular series for latitude librations and about 70 terms in the longitude angle and polar coordinates. In this determination, we found the non-negligible amplitude of the three modes of free physical libration. The determined amplitudes become 1.296" in longitude (after correction of two close forcing terms), 0.032" in latitude and 8.196" X 3.312" for the wobble, with the respective periods of 1056.13 days, 8822.88 days (referred to the moving node), and 27257.27 days. The presence of such terms, despite short damping times of 104 to 106 yr, suggests the existence of some source of stimulation acting in geologically recent times.

Keywords: Libration, Moon

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# THE THEORY OF THE MOON ROTATION AND DETERMINATION OF FOURTH MODE ITS FREE PHYSICAL LIBRATION

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**Resume.** In result of the comparison of our analytical theory of lunar physical libration, in particular the free librations, and available now, the empirical theory of the Moon's rotation (Rambaux, Williams, 2011), we have identified period, amplitude, and the initial phase of the forth mode of free libration of the Moon, caused by liquid core.

**Analytical theory.** The main study here is a construction and development of a highly accurate analytical theory of physical libration of the two-layer Moon (with uniform ellipsoidal liquid core and non-spherical elastic mantle). The core of the Moon is modeled by ellipsoid with an ideal homogeneous fluid. The mantle is considered as non-spherical solid body. The theory is developed on the basis of the canonical equations in Andover - Poincare variables and by special methods of the perturbation theory on construction of quasi-periodic solutions and investigation of their vicinity (based on the relevant equations in variations). The tables of values of the amplitudes and periods of forced and free librations for Andoyer ? Poincare variables describing the libration of the Moon and the core, for the variations of the components of the angular velocity of rotation of the Moon and the angular velocity of rotation of the coordinate system of Poincare (with respect to which a simple fluid motion is determined) have been obtained and studied. In first we have studied contributions in librations of the Moon of the second harmonic of selenopotential in accordance with the modern Selena model of gravitational field of the Moon (Matsumoto et al., 2010). The novelty of the theory and its practical significance are determined by the following principal provisions:

1.New forms of equations of physical libration of the two-layer model of the Moon (in particular in Andoyer ? Poincare variables) and new methods for their study; 2.Highly accurate description of the developments of spherical functions of the coordinates of the Moon, in the expression of the force function; 3.The new two-layer Mizusawa model of the Moon and Selena model of the gravitational field of the Moon; 4.Cassini rotation of the Moon, forced and free librations of the Moon in analytical form and their tables; 5.Dynamical effects in forced and in free librations caused by a liquid core; 6.Dynamical effects in forced and free librations of the Moon caused by its elasticity; 7.Determination of the forth mode of free libration caused by the liquid core; 8.Identification of some terms of modern Rambaux-Williams empirical theory.

**Determination of the period, amplitude and phase of the fourth mode of the free libration of the Moon caused by the liquid core.** We have been compare free libration terms from our analytical theory with some unidentified terms from empirical theory (Rambaux, Williams, 2011). In results 8 unidentified terms for classical variables in empirical theory were explained and amplitude, initial phase of the Moon free libration have been determined. The period of free libration of the pole of the Moon with liquid ellipsoidal core appreciated by us in 205.7 yr. The amplitude and initial phase of Poincare long-periodic argument of the free libration in pole motion due to liquid core have been determined in 0"0395 and -134 degrees (for initial epoch 2000.0 JD). In accordance with developed analytical theory this period corresponds to the sum of dynamic compressions of the core in 7.24x10(-4), that is in agree with seismographic data and data of laser observations (Barkin, Hanada et al., 2012). In assumption about similarity of ellipsoidal core and the entire Moon we have obtained the estimations of oblatenesses of the liquid core: 4.42x10(-4) and 2.83x10(-4).

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Keywords: Moon, rotation, resonance, free librations, LOD

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PPS03-04 Room:202 Time:May 20 15:00-15:15

# A simulation study for constraining the lunar internal structure by geodetic and seismic data

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Internal structure and composition of the Moon provide important clue and constraints on theories for how the Moon formed and evolved. The Apollo seismic network has contributed to the internal structure modeling. Efforts have been made to detect the lunar core from the noisy Apollo data (e.g., [1],[2]), but there is scant information about the structure below the deepest moonquakes at about 1000 km depth. On the other hand, there have been geodetic studies to infer the deep structure of the Moon. For example, LLR (Lunar Laser Ranging) data analyses detected a displacement of the lunar pole of rotation, indicating that dissipation is acting on the rotation arising from a fluid core [3]. Bayesian inversion using geodetic data (such as mass, moments of inertia, tidal Love numbers k2 and h2, and quality factor Q) also suggests a fluid core and partial melt in the lower mantle region [4]. Further improvements in determining the second-degree gravity coefficients (which will lead to better estimates of moments of inertia) and the Love number k2 will help us to better constrain the lunar internal structure. Such improvements will be made by future lunar missions including Japanese SELENE-2. A preliminary simulation study shows that the k2 accuracy of better than 1% is anticipated by the SELENE-2 differential VLBI mission for which one of the radio sources is fixed on the moon serving as the reference to determine the orbiter's trajectory.

We carried out a feasibility study using Bayesian inversion on how well we can constrain the lunar internal structure when such improvements are made on the geodetic data. It is difficult to tightly constrain the internal structure from the geodetic data only because there are trade-offs among crust, mantle, and core structures. However, when combined with the existing Apollo seismic data which constrain the structures of crust and mantle, such geodetic data will contribute to narrow the range of the core structure models. We will discuss the impact of the crustal structure uncertainties on the estimation of the core structure, and also the assumption we have to place on the mantle structure in order to recover the core structure.

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Keywords: Moon, gravity field, tidal Love number, internal structure, VLBI, SELENE-2

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# Investigation of lunar interior volatile from the state of the core and the lower mantle: SELENE-2 VLBI-LLR proposals

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Existence of volatiles in lunar deeper interior should change lunar evolution scenario of hot origin: from the giant impact through the magma ocean. Liquid metallic core would be caused by significant amount of sulfur to lower core melting temperature, whereas low-viscosity lower mantle would suggest the presence of water.

The effect of lunar tidal deformation can be detected by gravity change, through degree 2 potential Love number, $k_2$, which could constrain the state of the core and viscosity of the lower mantle of the Moon. We propose VLBI radio (VRAD) sources both on the lander and the orbiter of SELENE-2. Using same-beam (or two-beam) multi-frequency VLBI, we can measure low-order gravity changes, and estimate $k_2$ with uncertainty below 1% through precise orbit determination of the orbiter of relatively higher altitude ($>$ a few 100km). When the core radius is 350 km, $k_2$ value changes by about 5% between liquid and solid cores. And if the core size is constrained by SELENE-2 seismometer, contributions of lower mantle and core on $k_2$ would separated.

Dissipations of lunar librations also depend on core and lower mantle states. We also propose a Lunar Laser Ranging (LLR) reflector on SELENE-2 lander. With pre-existed reflectors, latitudinal component of lunar libration and its dissipation will be measured. Among LLR parameters, $k_2$ and core oblateness are coupled. Once $k_2$ is determined, we can determine core oblateness, which would also constrain core and lower mantle states.

Keywords: origin and evolution of the moon, lunar lower mantle, lunar core, tidal love number, lunar rotation, lunar volatiles

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PPS03-06 Room:202 Time:May 20 15:30-15:45

# METHOD OF ANALYSIS OF EXISTANCE OF THE ZONES OF LOWER SEISMIC VELOCITIES OF PLANETS AND SATELLITES

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In connection with the planned space missions to the Moon and Mars to study the internal structure of these celestial bodies by seismic methods seem to be very relevant theoretical studies of possible features or internal structures of these celestial bodies. The mechanism of forced oscillations of the core and mantle of the celestial bodies and study of their geodynamic and geophysical consequences gives us opportunity to study some inner structures of the Earth, the Moon and Mars and some others celestial bodies (in particular the zones of lower seismic velocity).

The mechanism of forced relative oscillations, displacements and rotations of shells of given celestial body under the action of the gravitational attraction of external celestial bodies [1] in the last decade has attracted wide attention of specialists in various geosciences and planetary science. On the base of this geodynamical mechanism and model some fundamental problems of geodynamics and celestial mechanics, geology, geodesy and geophysics have been solved in last 10-15 years. Here we study the possible role of forced relative oscillations of the core and mantle of the Earth and Mars, some satellites of Jupiter and Saturn in the formation of the shell structures (layers) of these celestial bodies. First and foremost, the existence and nature of the zones of low seismic velocities (LVZ), as well as the zones of the extreme radial deformation of the spherical layer of the mantle. For the Earth and Mars the zones of low seismic velocity correspond to the spherical zones of the mantle for which the displacements of the particles due to gravitational action of displaced core are either small or absent and the change in directions of radial displacements is observed.

Our results suggest that for the Earth, the origin of the low-velocity zone and its position (with mean depth about 144 km) is determined by the mechanism of forced displacements of the Earth's core. A similar low-velocity zone at about 300 km depth we have been predicted for Mars. The style of deformations of the mantle layers of the Mars and the Earth (and probably for Venus) have much in common. Therefore the existence of the low-velocity zone of the planet Mars, at a depth of 300 km, seems quite real. Similar studies we fulfill now for some synchronous satellites of Jupiter and Saturn (Io, Ganymede, Europa, Titan, Enceladus, etc.) to identify zones of extreme radial deformations that occur during forced relative radial oscillations of the shells. In the report the preliminary findings on the positions situation of the zones with extreme largest deformation and the zone in which the deformations are small or absent are discussed.

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Keywords: Core, motion, mantle, deformation, existence, LVZ

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PPS03-07 Room:202 Time:May 20 15:45-16:00

# Some technological problems in development of a small Telescope for selenodesy and geodesy

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Observations of the lunar rotation are one of the essential and basic selenodetic observations for investigation of the interior of the Moon as well as those of gravity fields, and high accuracy of the observations have a potential to detect signals related to the structure of lunar deep interior including the core. Technological development dedicated to highly accurate observations for the Moon, on the other hand, can return to the application to the Earth again. We are developing a small telescope for observations of Lunar rotation with a target accuracy of 1 milli arc second, and it has a potential to observe deflection of the vertical on the ground with high accuracy. This accuracy is epochal also for the observation of the deflection of the vertical even if it may be deteriorated to some extent by atmospheric fluctuations etc.

Major problems in the observations on the Moon are large temperature change and the difficulty of adjustment. We developed an objective using a diffractive lens in order to loosen the condition of the temperature change, and we adopted PZT (Photographic Zenith Tube) having a horizontal reference plane of a mercury surface in order to realize an adjustment-free system. Observations on the ground, on the other hand, are mostly affected by ground vibrations and atmospheric fluctuations. The effect of temperature change is not very large and it is relatively easy to control the temperature around the tube.

As the results of laboratory experiments, it is possible that the vibration of the mercury surface caused by the ground vibrations lead to fluctuations of star positions on CCD as large as 1 second of arc. The amplitude of the fluctuations depend on the amplitude of the ground vibrations and the depth of mercury pool. We can reduce the effect of the vibrations by making the mercury pool shallow down to the minimum depth. In the case of the mercury pool of 64mm diameter, the depth of 0.5mm is the minimum depth judging from our experience. Shallower pool will shorten the life time and will be affected more easily by the tilt.

It is important to keep the proper period of the mercury pool away from the period of ground vibrations in order to avoid the resonance. It is also effective to lengthen the integration time, and it can improve the reliability of the mean value of the center of a star image by statistical procedure. Adaptive optics is widely used for compensating the effects of atmospheric fluctuations and for obtaining sharper images approaching the diffraction limit. The adaptive optics, however, is not always effective for the astrometric telescope like PZT because it is possible to shift the center of star image by deformable and tip-tilt mirrors.

We investigate the cause of fluctuations which can affect the observations on the ground, and we explore the possibility for a new effective observations with the telescope like PZT.

Keywords: lunar rotation, deflection of the vertical, PZT, mercury surface, ground vibration, thermal deformation

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PPS03-08 Room:202 Time:May 20 16:15-16:30

# New findings in Earth‘s sciences

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An excitation mechanism and forced relative translational oscillations, swing and rotation of the Earth shells (and other planets and moons) under the gravitational action of external celestial bodies is a powerful source of endogenous activity with pronounced cyclical manifestations at different time scales endogenous energy of the planet as an open thermodynamic system (represented by the scheme with threads of different types of energy, the entropy and others) made it through gravitational interaction of external celestial bodies. The energetic of this mechanism allows to specify the energy budget of the Earth in comparison with contributions of another acting mechanisms. The estimates of the power dissipation for a viscous-elastic deformation of the Earth’s mantle caused by the relative displacements of the center of mass of the mantle and core have been obtained. The inversion phenomenon of the Earth’s climate changes with respect to Northern and Southern hemispheres its contemporary manifestations are analyzed and discussed.

For analysis the general global astrogeophysical factor - Earth’s rotation rate (ERR) was used. The important role of the lunar-solar gravitational tides for weather, climate and geophysical processes in the atmosphere, oceans, and other geospheres and in the biosphere has been shown. The role of tides by using the ERR has been demonstrated on the base of observational data on precipitation in the Indian monsoon period, in the formation of tropical depressions and typhoons, in the perturbations of Earth’s magnetosphere and during strong earthquakes, as well as in medical terms cardiovascular system patients and other diseases. Earth’s rotation rate is so high compared to the speed of the proper motion of the tidal waves in the solar system of reference, we are dealing only with quasi-diurnal waves and their sub-harmonics. At spectral or harmonic analysis measuring low frequency waves of gravitational tides also merge with the harmonics of daily or annual thermal tides and become virtually invisible to learn. To low-frequency tidal waves are not lost in the spectral analysis, it is necessary to exclude the effects of rotation and revolution of the Earth, that is demodulated time series measurements. It is enough to fix the period of measurement (one measurement: for a day, to prevent rotation of the Earth, or the year to avoid the annual revolution of the Earth). Even before it was established that the weather changes during the lunar month is synchronized to within 0-2 days from the extremes of the EER, describing the motion of the Moon and the Earth around the barycenter. We have detected and studied a week and semi-month lunar tidal waves in the spectrum of the angular momentum of the atmosphere. Estimates have shown that classical gravitational tidal forces can not explain the tremendous energy associated with variations of the angular momentum of the atmosphere. We discuss possible role of the resonance effects in origin observed cyclicities in natural processes. Big prospects here open in dynamical and empirical studies of new tides the nature of which is connected with action of mechanism of forced oscillations of the Earth shells in gravitational field of the Moon, the Sun and all another bodies of solar system. In particular it was shown that mechanism of new tides for discussed in report frequencies and periods of oscillations generates phenomenal power of dissipations (and variations of planetary heat flow) of the order 10 (15) Wt. This energetic is sufficient for explanation of observed activity and cyclisities of all planetary processes.

Keywords: angular momentum, atmosphere, magnetosphere, tidal waves, climate changes

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# Geodetic consequences of the northern drift of the Earth's core and their confirmations in the space geodesy data

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In the last 10 - 15 years the Russian and Chinese scientists have been fulfilled geodetic studies of contrast changes in the shape of the Earth, in the northern and southern hemispheres. In the works of Chinese scientists were executed empirical studies of secular variations of volumes of the northern and southern hemispheres, secular changes in the lengths of the circles of latitude in the southern and the northern hemispheres, the secular changes in the mean radius of the northern and southern hemispheres on the basis of current data space geodesy and VLBI data. For what was made a careful selection of monitoring stations and analyzed long series of high-precision measurements of the radii of stations and their displacements in the basically Earth's reference frames. In the works of Prof. Y. Barkin and colleagues (starting from 1995 -1996) the modern geodynamics of the forced librations of the core and mantle of the Earth by the gravitational attraction of external celestial bodies has been developed and has been given wide applications in geosciences, in particular in geodesy.

The most important result is the prediction and justification of the existence of the secular trend of the center of mass of the Earth as a consequence of the secular northern drift of the core of the Earth relative to the mantle. The wide geodynamic, geophysical, geodetic studies and their role in climatic change, seismic and volcanic activity, and in many other natural processes have been fulfilled in the last 15 years. Modern DORIS satellite observations (in space geodesy) indicate the existence of the secular polar drift of the center of mass of the Earth (to the North) at 5.29 mm / year. This drift reflects the Earth's core drift (drift of the center of mass of the core relatively to the center of mass of the mantle) at a rate of 27.4 + / -0.8 mm / year (Barkin, 2005). Gravitational effect of the shifting core causes deformations of all layers of the mantle and various offsets of its points (both on the surface and inside the Earth). As a result of these deformations the mean radius of the northern hemisphere increases with secular velocity about 0.17 mm / year, and the mean radius of the southern hemisphere on the contrary, decreases with the same magnitude of velocity - 0.17 mm / year (Barkin, 2005, 2011). As a result of careful processing of satellite data and VLBI observations at 845 stations in a recent paper (Wenbin Shen et al., 2012, private communication) were obtained related values of 0.46 + / -0.01 mm / year and -0.19 + / -0.01 mm / year, respectively. The theoretical value of the greatest secular velocity of lengthening of latitudinal circles in the southern hemisphere at latitude 45 S is 4.17 + / -0.12 mm / year, and in the northern hemisphere the secular velocity of shortening of latitudinal circle (for latitude 45 N) is - 4.17 + / -0.12 mm / year. According to the processing data of GPS observations Jin Shuanggen in 2005 has obtained related values of secular velocity in 4.2 + / -0.5 mm / year and 10.0 + / -1.0 mm / year for the corresponding hemispheres (Jin, 2005; Barkin, Jin, 2006 , 2007). Thus the main trends of geodetic changes of the northern and southern hemispheres has obtained a nice explanation. Revealed an asymmetry in the shape of the Earth changes are apparently related to the formation of zones of rifting and subduction zones in their asymmetrical arrangement in the northern and southern hemispheres. Also in our joint work we have fulfilled studies of the dependence of the mean radius of the Earth and the mean velocity of secular change in the length of the latitudinal belts from the latitude (Barkin, Jin, 2007; Wenbin Shen, 2012). Theoretical results and data of satellite observations are in good agreement. The report also discusses the expected related phenomena on the Moon and Mars and the possibility of theoretical prediction and detection by high-precision observations in the planned space missions.

Keywords: drift of center of mass, secular geodesy variations, mean radiuses of hemispheres, the Earth, Mars

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PPS03-10 Room:202 Time:May 20 16:45-17:00

# Manifestations of tides in geospheres and in the biosphere

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The gravitational tides in the atmosphere are recorded as the waves with the periods close to one day and its sub harmonics. Some of them are usually interpreted as the proper atmospheric modes. They commonly have either the amplitude or the frequency modulations. A new explanation of the quasi-diurnal and quasi-semidiurnal tides lines in the spectrum of the atmospheric angular momentum and other atmospheric characteristics is proposed. The role of gravity tides in the dynamics of the atmosphere and the ocean is underestimated. The reasons of a wrong estimation of a role of the tidal phenomena in geophysics are explained.

It‘s shown here that zonal tidal forcings with periods of ˜3.5 and ˜7 days determine processes in the atmosphere (weather change, formation of tropical depressions, cyclones (including typhoons), monsoon precipitation periodicity, in the magnetosphere (increasing geomagnetic activity), in the lithosphere (seismic-disturbances, including earthquakes) and increase the medical statistics in cardio-vascular illnesses and in other ones as well (see below). Luni-solar gravitational tides correlates absolutely with Earth rotation rate (ERR) and can be calculated for any time in advance. The correlation of 3,5 and 7 days periods of weather change with the same periods of human health parameters has been established. That has been demonstrated during International Conference ”Space Weather Effects on Humans: in Space and on Earth” (Moscow, from 4-8 June 2012) and II Russian Conference on chronobiology and chronomedcine (in the frames of XIV World congress ¥¥¥”Health & Education millennium¥¥¥” (14-17 November 2012, Moscow, Russia).

We discuss some new physical processes which are very important for Earth‘s climate. An example of our analysis of a number of annual rings of Japanese cypress, 800 years (data for 1100-1920 taken from the book Selected papers on Climatic Change written by well known Japanese climatologist H.Arakava) is given. This analysis shows a clear link of QBO periods with periods of El Nino - Southern Oscillation and the Chandler period (CP) first mentioned by Sidorenkov. Major and decisive role for the Earth as an open system, are external to it gravitationally interacting system of ”oscillators” (Moon, Earth, Sun and planets) and gravity (as well as for the thermal atmosphere of the Earth) tidal forces. The interaction of the tides of all types and multiple binding modes with phase transitions of water vapor forms quasi-three-dimensional structures. Such structures have been discovered on space-time sections, constructed from orbital observations from satellites. We suggest new concept of tidal phenomena in the atmosphere, which is in conflict with the existing classical theory of Chapmen and Lindzen

After conducting field experiments in southern India, and at the equator in the Indian Ocean in March and June 1990 within the framework of the international program DYANA, observing a wide range of fluctuations of the ozone layer and the middle atmosphere of the author formulated a working hypothesis - the atmosphere is a system of oscillators interacting with each other and with oscillators in other geospheres and in space.

A new approach to the problem of long- and short-term prediction of atmospheric phenomena should be done, taking into account all types of tides and their multiple modes. Results of successful experiments on modification of meteorological processes are given.

So, the 1st main conclusion must be done that atmosphere/ocean phenomena are deterministic processes rather than stochastic ones. That leads inevitably to the 2nd important inference: so called the time limit of forecasting (f.e. for weather change) is not exist! 3d one is: we deal with open physical system that is resonant one. Mentions above will open a way to high technology of weather and climate modification.

Keywords: Luni-solar gravitational, Manifestations of tides, Earth‘s climate., weather modification

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# Measurements of Martian rotational variations by space geodetic techniques

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Variation of planetary rotation provides us information concerning both the interior structure and the surface mass redistribution. Such information is valuable for elucidating not only present condition but also evolution of a planet as a system. Precession and nutation of Mars reflect the present status of the core-mantle sub-system, besides length-of-day variation and polar motion of Mars are induced by variation of the atmosphere-cryosphere sub-system.

Two-way tracking of orbiters on Mars were executed to elucidate the physics of Mars. Precession and length-of-day variation have been measured by means of tracking data of Viking 1 and 2, and Mars Pathfinder. The results of the Love number k2 obtained by two Martian explorers, namely, Mars Global Surveyor (MGS) and Mars Odyssey, predict existence of a liquid core inside Mars. Seasonal variations of the polar caps on Mars were estimated mainly based on the laser altimeter data on MGS in conjunction with gravity data. Although Mars rotation observations by two-way tracking have produced scientific results as shown above, these measurements had limitations in terms of accuracy within the framework of traditional technologies concerning space geodesy and astrometry. Thus, the new configurations of orbiter-to-lander tracking had been proposed for two Martian explorers. To achieve the accuracies in the order of 1 mas (mill-arc second) to detect Martian rotation variation, orbiter-to-lander tracking were proposed for NetLander and ExoMars.

A Japanese research group has recently started to plan a new Martian explorer; MELOS (Mars Exploration with Lander-Orbiter Synergy). As one of the missions of MELOS, we are proposing areodetic observations using space geodetic techniques such as four-way Doppler measurements and inverse VLBI (Kawano et al., 1999). By measuring the Mars rotation with higher accuracy, we will be able to determine the state of the core (liquid or solid) more clearly, estimate its radius if it is liquid, and figure out the quantities of seasonal surface mass redistribution. Four-way Doppler measurements (FWD) are ranging rate measurements of target spacecraft via relay spacecraft. Utilizing the heritage of FWD by SELENE, we plan to track the multi-landers of MELOS relayed by the MELOS Orbiter. The expected accuracies for these observations are almost in the same order as that in the case of orbiter-to-lander tracking. We also introduce a new technology called inverse VLBI. One ground radio telescope, not a VLBI network, observes both the orbiter and the landers with same-beam or switching of the antenna. The signals from the landers are coherently locked with those of the orbiter, and phase differences between the two spacecraft are also measured at the orbiter. The functions of the orbiter and the landers may be exchanged depending on the limits of resources including mass and electric power of each spacecraft, although, the precisions of the measurements are independent of such configuration changes. One of the remarkable characteristics of inverse VLBI is that the theoretical accuracy of positioning depends only on the observation frequency and does not depend on the distance between the radio sources and the ground stations. Therefore, X-band observation of inverse VLBI will achieve the accuracy of 0.3 mm which is much better than that of FWD, RARR, and differential VLBI. Including the systematic phase noise, the accuracy for the rotation is estimated to be better than 3 mas. The inverse VLBI system, however, needs to calibrate the phases through links with higher accuracies.

Keywords: Mars, rotation, space geodesy, satellite-to-satellite tracking, VLBI

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PPS03-12 Room:202 Time:May 20 17:15-17:30

# A preliminary observation of 531-day period in wobble of the polar motion

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Previous studies show that the polar motion contains two dominant components, namely the annual wobble (AW) with a 12-month period and the Chandler wobble (CW) with a 14-month period. Some scholars consider that the frequency of the CW varies with its amplitude; some scholars consider that CW has double or multiple frequencies; some scholars consider that the frequency of CW is invariant. In 180s, a 530-day-period wobble in polar motion was marginally detected. Since then, we did not find literatures addressing this wobble period from any kind of observations. In this preliminary study, we apply the ensemble empirical mode decomposition (EEMD) method to analyses of two kinds of observations. First, applying EEMD to two polar motion time series, the EOP C04-05 series with one-day sampling interval spanning 1962 to 2012 and the POLE2010 series with one-month sampling interval spanning 1900 to 2011, we observed a 531-day-period (about 0.68683 cpy) wobble and a 530-day-period (0.68913) wobble, respectively. Noting that the estimated amplitudes and frequencies of this wobble from the two series are different from each other, we consider that the difference is caused by the relative poor quality of the POLE2010 series during 1900-1961. Deleting the poor quality data sets, we obtain the 531-day-period wobble from both time series. Our results show that the frequency modulation of the CW may greatly suppress the 531-day-period wobble so that it cannot be observed in conventional direct power spectra of the polar motion series. Second, applying EEMD to two superconducting gravimeter records with a length of about 15 years and one-day sampling interval, we also observed the 531-day-period wobble. If the 531-day-period wobble really exists, it might be caused by the fluctuations of global atmospheric and oceanic angular momentums. Further investigations are still in progress. This study is supported by NSFC (grant No. 41174011), National 973 Project China (grant No. 2013CB733305) and NSFC (grant No. 41210006, 41128003, 41021061, 40974015).

Keywords: 531-day-period, wobble, polar motion, ensemble empirical mode decomposition, EOP and POLE series, superconducting gravimeter records

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PPS03-P01 Room:Convention Hall Time:May 20 18:15-19:30

# Optical Response Simulation of Corner Cube Reflectors for SELENE2 Mission

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The object of these simulations is clearing up the criterion for the Corner Cube Prism (CCP) and the Corner Cube Mirror (CCM) in order to measuring the distance from the Earth to the Moon in cm order. In case of the CCP, the refractive index inhomogeneity restricts its size to small (˜10cm), so we did not calculate the effect of any deformation. In case of the CCM, we calculated both effects of the Moon gravity deformation and the thermal deformation.

The Optical responses were calculated with CodeV (Synopsis, Inc.), and we did not consider DAO (Dihedral Angle Offset), because the common optical simulation software cannot calculate its effect.

The Optical response criterion is that the encircled energy within 3.5mrad (half angle) $>$ 50%, where 3.5mrad is equal to the minimum deflection by the velocity aberration without DAO. The velocity aberration deflect 3.5-7mrad from the Laser emitted direction according to the relative speed between the Earth and the Moon.

Keywords: corner cube reflector, laser ranging, PSF

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# Developement of the telescope for ILOM (In-site Lunar Orientation Measurement) using the DOE (Diffractive Optical Elemen

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ILOM demands the very high performance to the optical system in order to realize the determination of star positions with 1 milli arc second accuracy on the Moon whose environmental condition is very fierce. There are several causes that degrade the optical performance and the most effective cause is the change of the environmental temperature. The temperature change causes the change of lens shape and the change of the refractive index of each lens material and the later is much dominant. The optical system of ILOM is the refractive system so we have to reduce the chromatic aberration using so-called the low dispersion glass, but this type glass has a much bigger dn/dt (the index change for the temperature change) than the normal glasses. In result of this, the optical system using the low dispersion glass lens becomes very sensitive to the change of the environmental temperature.

So we developed the optical system (objective lens) using the DOE (Diffractive Optical Element). Using the DOE, we can reduce the chromatic aberration without the low dispersion glass lens. So we can develop the objective lens that is very tolerant to the environmental temperature change because we can design the objective lens using small dn/dt glass lens only.

Keywords: ILOM, DOE

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PPS03-P03 Room:Convention Hall Time:May 20 18:15-19:30

# Planetary Tectonic System (#2): Classification for the Search of Life Beyond Earth

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For life to initiate, diversify, and flourish, it requires a continuous nutrient supply, metabolism with continuous reactions to gain energy, and self-duplication [1; also see Shigenori Maruyama, this conference]. Based on our understanding of the evolution of Earth, which includes the Cambrian explosion [1; also see Shigenori Maruyama, this conference], these conditions can be optimally met through a planetary tectonic system (PTS) that is composed of a nutrient-enriched continental landmass, an ocean, tectonic structures such as rift systems that act as conduits for the migration of volatiles and heat energy, as well as the delivery of toxic elements (e.g., radiogenic nuclides) for the diversification of life (evolution requires perturbations from normal conditions), and a sunlit planetary surface [1].

Since a PTS provides the road map for the search for life beyond Earth [also see, Maruyama and Dohm, this conference], we propose a classification of planetary bodies with certain PTSs unfolded through geological investigation using existing planetary data sets.

Such a classification is not only based on the distance of the planetary body from the Sun and its composition, but also by its characteristic PTS. This is important, because the birth place of life and evolution is controlled by an optimal PTS as exemplified during the Cambrian explosion [1; also see Maruyama and Dohm this conference]. Without understanding PTS, it is impossible to target possible candidates of life-sustaining habitable environments both in and outside our solar system.

The types of PTS are: (1) Earth-Cambrian-explosion [1; also see Maruyama, this conference], (2) Ice-house Mars [2,3], (3) Hot-house Venus [3,4], (4) Rigid Mercury, (5) Gaseous-giants, and (6) Frigid, dynamic, and/or hydrologically exotic satellites. Others types (e.g., Kuiper belt planets and dwarf-planets) could be added in the future.

Detailed characteristics of the various PTSs will be detailed at the conference.

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# Luni-Solar Tides in the Earth Atmosphere

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The gravitational tides in the atmosphere are recorded as the waves with the periods close to one day and its subharmonics. Some of them are usually interpreted as the proper atmospheric modes. They commonly have either the amplitude or the frequency modulations. A new explanation of the quasy-diurnal and quasy-semidiurnal tides lines in the spectrum of the atmospheric angular momentum (AAM) and other atmospheric characteristics is proposed. The role of gravity tides in the dynamics of the atmosphere and the ocean is underestimated. The reasons of a wrong estimation of a role of the tidal phenomena in geophysics are explained.

We have calculated the power spectrum of the complex series h1+ih2. The resulting spectrum has been analysed. . The most striking detail of the spectrum of h1 + ih2 is a blurred maximum of the spectral density at ?0.85 cpd. Its height is indicative of a high power of h1 and h2, and the width shows considerable ?uctuations of the period. What lies behind this phenomenon and why does the atmospheric circulation produce strong noise in this frequency range? Due to our discovery, it becomes clear why the role of gravity tides in the dynamics of the atmosphere and the ocean is underestimated. The fact is that all hydrometeorological and hydrophysical characteristics are measured at moments of mean solar time, which is the hour angle of the Sun determined by the Earth diurnal rotation and annual revolution. That is, by default, a frame of reference tied to the Sun (referred to hereafter as the solar frame) is used in this case. In this frame, the apparent velocity of a tidal wave is the sum of its proper velocity and the translational velocity. The latter arises due to the Earth diurnal rotation and the Earth annual revolution around the Sun. Its magnitude is very high compared with the proper velocities of tidal waves Therefore, in the solar frame we deal only with quasi-diurnal tidal waves and their subharmonics. In the spectral (or Fourier) analysis of observations, the low-frequency waves of gravity tides are di?cult to distinguish from the harmonics of diurnal or annual thermal tides and are nearly imperceptible for study. Hydrometeorologists construct synoptic maps or time-coordinate sections with a ?xed geographical grid of parallels and meridians. That is, by default they use a frame of reference tied not to the Sun, but rather to the stationary Earth surface. In this frame, the Earth diurnal rotation and orbital revolution are eliminated, while the proper motion of tidal waves is only present. Hydrometeorologists give attention only to fast quasi-diurnal tidal waves predicted by the theory. The proper motion of tidal waves remains unnoticed. All slow waves moving over the Earth surface, including tidal waves, are interpreted as usual atmospheric or oceanic waves. To detect low-frequency tidal waves in spectral analysis, we have to eliminate the e?ects of the Earth rotation and revolution demodulate measured time series. For this purpose, it is su?cient to ?x the time of measurements (one measurementa day to eliminate the Earth diurnal rotation or one measurement a year to eliminate the Earth annual revolution). As a result, weekly and semimonthly lunar tidal waves were detected in the spectrum of the atmospheric angular momentum. This method opens up new opportunities for studying the e?ects of lunisolar tides and functions of the Sun barycentric motion.

Keywords: Luni-solar gravitational, The gravitational tides

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# Kaula's rule and the scaling law of the Kaula constant in the lunar-planetary gravity fields

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Gravity fields of the moon and planets are modeled as the sum of spherical harmonics of various degrees/orders, and their coefficients are called as the Stokes' coefficients. These coefficients with degrees and orders complete to a few hundreds have been estimated using the tracking data of artificial satellites such as GRACE (the earth), SELENE and GRAIL (the moon). High degree coefficients show fine structure of the shallow mass distribution, and low degree coefficients reflect global scale mass distribution of the body. Kaula's rule-of-thumb predicts that the Stokes' coefficients are inversely proportional to the square of the degree n of the spherical harmonics. In this study, I confirmed that this is the case for the moon, the earth, Mars and Venus. Smaller coefficients for higher degrees mean that the long wavelength components have larger amplitudes.

Here I refer to the factor to link 1/n2 to the Stokes' coefficients as the Kaula constant. The smaller celestial body is considered to have a larger Kaula constant, and they are considered to obey a scaling law that the coefficient is inversely proportional to the square of the surface gravity of the body (in the original paper by. Kaula [Kauka,1963], the constant is suggested to scale with R4/M2, where R and M denote the radius and the mass of the body, respectively). This scaling law is confirmed to hold true for the moon, Mars, Venus, and the earth. Departure from this scaling law would imply some difference of the physical properties (such as viscosity) of the material that makes up the interior of the body. Recent data on the gravity field of Mercury taken by MESSENGER seem to indicate such a departure, which may reflect the unusually large relative radius of the metallic core of Mercury.

The lunar farside and nearside are known to be very different, i.e. the nearside has thin crust and flat terrain, whereas the farside has thick crust and rugged terrain. There are several hypotheses for the origin of such lunar dichotomy, and many of those suggest some difference in thermal history between the two sides. Such a difference can be studied with the gravitational field. Here I compared the Kaula constant of these lunar two hemispheres by creating two hypothetical moons, those composed of only farside and only nearside. The Kaula constant of the farside showed slightly larger value than the nearside, suggesting colder internal temperature of the lunar farside.

Keywords: scaling law of the kaula constant

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# A time scale of true polar wander on a quasi-fluid planet: Effect of a low-viscosity layer inside a mantle

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In this study, model calculation on long-term polar motion accompanied by viscoelastic deformation are performed in order to investigate the effect of a low-viscosity layer inside a mantle of a solid planetary body on a time scale of true polar wander. Here a planetary body is supposed to be similar to the Earth or Mars, but with the low-viscosity zone. The most important key is dependence of the viscoelastic response on this low-viscosity layer. On the other hand, note that deformation process in here is regarded to be incompressible for solving normal modes of viscoelastic Love numbers. For the sake of the calculation based on this assumption, the interior structure is still simplified to some extent except for the presence of the low-viscosity zone. However, this simplification does not affect the validity of the subsequent discussion.

In this calculation, the quasi-fluid approximation is applied so that the polar motion equation can be integrated just as a nonlinear one. The reason is that the linear approximation is not generally applicable to large polar motion of a magnitude of several tens of degrees as discussed here. Following the application limit of the quasi-fluid equation, load formation is assumed to be much slower than characteristic time scales of viscoelastic deformation. This approximation scheme has already been constructed by the author as well as some other researchers. The present study also deals with this integration in the same manner.

As a result, the above calculation indicates the fact that the time variation of a spin pole with the effect of the low-viscosity layer is faster compared to that without it. In addition, the result also reveals that, the shallower the low-viscosity zone is, the faster the polar wander speed is. The reason why the low-viscosity layer makes polar wander speed faster is because the behavior of this layer is like that of liquid even with respect to relatively short-term variation of external forcing. This corresponds to, in turn, faster hydrostatic readjustment to centrifugal potential perturbation, which shortens a time scale of variation in the moment of inertia tensor associated with that in the spin axis. Furthermore, variation of an oblate shape with viscous relaxation of this layer negatively depends on the thickness of the upper shell which elastically reduces the above-mentioned fluid-like displacement of the layer. This point assures that the effect of the low-viscosity layer on polar wandering is stronger if the upper shell is thinner, that is, this soft layer is shallower.

The calculation result shown above provides the conclusion that the presence of the low-viscosity layer in a planetary interior largely affects true polar wander even if the layer is relatively thin. The previous studies simplified mantle viscosity structure and ignored the low-viscosity layer inside. Unlike them, the present study demonstrates time evolution of true polar wander with the explicit effect of this specific layer. Although it has been pointed out in the past that such an easily deformable domain plays an important role in viscoelastic deformation induced by tide or load on the Earth, this point is the same in the case of secular rotational motion.

It should be noted, however, that the present calculation is also based on the assumption of incompressibility like the former one. Possible effect of compressibility might be required for more realistic calculation in the future.

Keywords: true polar wander, quasi-fluid approximation, low-viscosity layer, mantle