G42B-03 1410h INVITED

Accuracy Requirements for Moisture Observations Using Space Geodetic Techniques

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Most of our information about the structure and variability of moisture in the atmosphere comes from three operational sources: radiosondes, surface measurements of dew point temperature (convertible to relative humidity), and satellite measurements of brightness temperature in the infrared and microwave portions of the electromagnetic spectrum. These observing systems function synergistically, since no one system provides all of the information required for weather forecasting, climate monitoring, and scientific research. Notwithstanding the strengths of the operational composite moisture observing system, its shortcomings preclude significant advances in weather prediction, our understanding of atmospheric processes, and climate monitoring and prediction. In recent years, the use of space geodetic techniques for atmospheric remote sensing has been proposed, demonstrated and verified. Space geodetic techniques, especially techniques using the Global Positioning System, have certain attributes that strongly complement both operational (or soon to be operational) and research observing systems. NOAA's Forecast Systems Laboratory in Boulder, Colorado, has been evaluating techniques to retrieve integrated (total atmospheric column) precipitable water vapor (IPW) from zenith tropospheric signal delays since 1994, and use IPW in operational weather forecasting since 1997. As a result of these evaluations, the use of ground-based GPS-Met is expected to become operational within the National Weather Service over the next few years. However, space geodetic techniques will neither replace conventional observing systems, nor will they completely mitigate their deficiencies. In this talk, I will review the requirements for water vapor measurement accuracy, and show that this is application dependent. I will then discuss the strengths and weaknesses of the more common operational moisture sensing systems, and examine the attributes of some space geodetic techniques in this context.

URL: http://gpsmet.noaa.gov

G42B-04 1425h

Statistical distributions for water vapor parameters

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In assessing the accuracy of atmospheric information obtained from GPS observations, it is customarily (and conveniently) assumed that water vapor parameter estimates follow a Gaussian distribution. This assumption is clearly inappropriate for atmospheric information of interest such as wet zenith delays and wet delay gradients. Wet zenith delay estimates, for example, can present very asymmetric (skewed) distributions, and wet delay gradients are known to be nearly zero for most of the time accompanied by instances of relatively large values. A Gaussian distribution is a poor descriptor of such parameters. It is thus critical to determine the statistical basis of these atmospheric parameters for assessing the accuracy of GPS-based meteorological and climatological inferences and predictions. Comparisons of root-mean-square and other statistics that are based on a Gaussian assumption will lead to erroneous conclusions regarding the significance of these statistics. In this presentation, we will describe our theoretical approach and experimental studies to determine the statistics of water vapor parameters.

G42B-05 1440h

An error analysis of ground-based GPS slant-path residuals in a simulation study

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The accuracy of a method for obtaining slant-path delays from GPS double difference residuals is assessed in a severe squall line case. To retrieve the absolute value of phase delay along each ray path from GPS double differences, Alber et al. (2000) introduced "zero mean difference assumption" as an additional independent constraint. In this study, we perform an error analysis of the zero mean difference assumption by simulating "true" slant-paths defined by GPS receiver sites and satellite orbits in a high-resolution numerical weather prediction model. Using these slant delays we examine the validity of the so-called "zero mean assumptions". Despite the existence of a strong systematic bias associated with the surface cold front and severe convection, deviation from the zero mean difference assumption is on the order of a few mm in the unit of phase delay. This implies that slant-path residuals contain useful information on the spatial variability even when the zero-mean assumption is violated due to atmospheric conditions. The representative error is also investigated by comparing the vertically integrated zenith hydrostatic delay with the one averaged over all available zenith-mapped slant hydrostatic delays for a certain period of time. In spite of strong horizontal pressure gradient over the entire observation network, the representative error of zenith hydrostatic delay is about 0.1%.

G42B-06 1455h

Assessing the Accuracy of Slant Path Measurements Using a High Resolution Numerical Weather Model

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The ability to derive the delay induced by the neutral atmosphere along individual ray paths between a GNSS satellite and a receiving station can provide more detailed atmospheric information than zenith delay measurements. These line-of-sight integrals are often called slant path delays. Comparisons of slant water vapor measured by a pointing microwave radiometer and a collocated GPS receiver have shown better agreement than comparisons of the more commonly estimated zenith wet delay or precipitable water vapor. We have investigated the errors in slant path measurements using simulated observations from a high-resolution numerical weather model. This simulation described the passage of a squall line over a large portion of the United States Southern Great Plains region and had a high degree of both hydrostatic and wet delay variability. This simulation provided the opportunity to study the effect of realistic systematic and random errors on the slant delay sensing technique. We found that the largest errors in the estimated slant path values are systematic in nature and affect all neutral atmosphere delay estimates in the same way. This means that systematic errors introduce errors in the zenith delay estimates that are then mapped into the slant delay estimates. In contrast, the error in determining the anisotropic delay between a GNSS satellite and a receiving station is small. In summary, the retrieved slant path values can have periods where systematic errors result in significant errors of the estimated zenith delay, while the anisotropic variability of the atmosphere can still be recovered with high precision.

G42B-07 1510h INVITED

A Multi-Sensor Approach to Estimation of Line of Sight Tropospheric Delays

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We will discuss techniques for optimal integration of atmospheric measurements from collocated GPS receiver, pointed WVR, and a barometer, capitalizing on the unique strength of each sensor, and minimizing the impact of the sensor's weaknesses. The goal is to improve our ability to estimate line of sight (LOS) total atmospheric delay, which is required in support of certain high precision applications, such as radio science, and deep space navigation. The benefits from improved atmospheric sensing extend to many other applications such as geodesy and time transfer. The WVR's strength is its unparalleled accuracy in sensing the water vapor content along a given LOS, which produces the "wet" delay of a radio signal. But WVRs are incapable of measuring the contribution of the dry atmosphere to the delay, the fluctuations of which are a significant error source for certain radio science applications. GPS data is directly sensitive to the total tropospheric delay (wet plus dry). However, GPS analysis has so far failed to demonstrate comparable sensitivity to the WVR in resolving LOS delays. By using WVR to calibrate the line of sight wet delays affecting a collocated GPS receiver we will be able to tune the GPS estimation strategy to extract only the slowly varying dry delay component, improving the GPS retrieval accuracy. Barometric measurements may be used to further reduce the number of estimated parameters by modeling the zenith dry delay. The combined total delay provides the best estimate of the LOS total delay. We assess the performance of these techniques by processing experimental data from a Lamont, Oklahoma site, where all three instruments (GPS, WVR, barometer) were collocated, and describe the broad benefits of this approach.

G42B-08 1525h

Interferometry with GPS Low Earth Orbiters Occultations

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GPS signals reflected off the Earth surface can be detected by receivers aboard occulting Low Earth Orbiters (LEO). The geophysical information contained in such reflected signal, has been partially clarified for using radioholographic analysis. After calibration, occultation geometry and the troposphere have the main contributions to the relative delay between direct and reflected signal. The reflected-to-direct relative delay is a function of the location of the reflecting surface as well as the different effect of the troposphere on both ray paths. Information can be obtained from precise measurements of the interferometric delay, and by separating the geometric from the atmospheric effect. This talk presents novel results with centrimetric precision in carrier-phase reflected-to-direct relative delay from GPS to LEO occultations. The separation techniques will be discussed and potential applications of the interferometric delay to Ice surface topography, super-refractivity layer determination, marine boundary layer height detection will be given. Detection of super-refractivity conditions by the interferometric signal can lead to further refinements in the retrievals of lower atmospheric refractivity profiles where biases are known to exist.

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G42C MCC: 3005 Thursday 1600h

Geodesy of Terrestrial Planets II

(joint with P)

Presiding: **D E Smith,** NASA Goddard Space Flight Center**; T Van Hoolst,** Royal Observatory of Belgium

G42C-01 1600h INVITED

Geodesy of Amalthea and the Galilean Satellites of Jupiter

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An important scientific legacy of the Galileo mission is the determination of the masses and quadrupole components of the gravitational fields of the Galilean satellites. A final report of the mission results is given including values of GM (G is the universal gravitational constant, M is satellite mass), the gravitational coefficients J_2 and C_{22}, and the correlation coefficient μ between J_2 and C_{22}. The values of J_2 and C_{22} are deduced using the *a priori* assumption $J_2 = (10/3)C_{22}$.

The least squares method for fitting the Doppler residuals does not fix this ratio, but allows J_2 and C_{22} to vary independently and determines the correlation between them. The *a priori* assumption is consistent with the hydrostatic equilibrium of a satellite, but it does not require hydrostaticity. Values of μ show that J_2 and C_{22} are independently determined only for Io; the ratio of J_2 and C_{22} is consistent with a hydrostatic Io. J_2 and C_{22} are not independently determined for Ganymede even though there are both equatorial and polar flybys of the satellite. A quadrupole field is insufficient to fit the Ganymede data to the noise level. The additional signal is interpreted in terms of mascon anomalies at the surface of Ganymede. The gravitational coefficients, together with the assumption that the degree 2 gravitational fields of the satellites derive from their hydrostatic distortions to rotation and the Jovian tidal force, are used to infer the moments of inertia of the satellites and their internal structures. The mass and closest approach distance for Amalthea can be determined from Doppler data from the Galileo encounter of 5 November 2002. The final results indicate a density that is significantly smaller than the approximate 1000 kg m^{-3} density of water ice. The quadrupole components of Amalthea's gravitational field are undetectable in the encounter Doppler data.

G42C-02 1615h

Lunar Rotation, Orientation and Tides

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Many satellites exhibit synchronous rotation. The Moon is the most familiar example. For the Moon there is a) Lunar Laser Ranging measurements of tides and three-dimensional rotation variations and b) supporting theoretical understanding of both effects. The lunar rotational variations are up to 1 km while tidal variations are about 0.1 m, so the former effect has been more useful. Analysis of the lunar variations in pole direction and rotation about the pole gives moments of inertia, gravity harmonics, tidal Love number k_2, tidal dissipation (Q), and evidence for a liquid core. The experience with the Moon is a starting point for exploring the tides, rotation and orientation of the other synchronous bodies of the solar system.

G42C-03 1630h INVITED

Mercury's Interior From Geodesy of Librations

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Mercury offers a unique opportunity to use the equilibrium rotation state and librations about this state to investigate properties of its interior. In equilibrium, Mercury rotates at a uniform rate $\dot{\psi} = 3n/2$ (n = orbital mean motion) in a Cassini state with the spin axis displaced slightly from the orbit normal (obliquity near 1.6 arcmin), which displacement is induced by the precession of the orbit on the Laplacian plane. The spin axis, orbit normal, and normal to the Laplacian plane remain coplanar while the former two precess about the latter with the period of the orbital precession. If displaced slightly from this state, Mercury's spin will exhibit a free precession about the state with period near 1300 years and a free libration in longitude with period near 12 years. Tidal dissipation will damp both free precession and libration on time scales $<<$ the solar system age, so we expect to find Mercury very close to its equilibrium Cassini state where it remains during slow orbital variations because of an adiabatic invariant. The gravitational torque on the axial asymmetry is the restoring torque for the free librations when averaged over the orbit. This same torque causes a small forced libration in longitude (amplitude 20 to 40 arcsec) with an 88 day period due to the torque's periodic reversal around the orbit . It is desirable to determine Mercury's obliquity θ and the amplitude of its forced libration in longitude ϕ to very high accuracy, because their determination along with accurate values of the gravitational harmonic coefficients C_{20} and C_{22} can reveal whether or not Mercury's core is molten by determining the ratio C_m/C. C_m and C are the maximum principal moments of inertia for the mantle and entire planet respectively, where both moments of inertia are determined independently. This assertion relies on the axial asymmetry being due to the mantle alone, where the 88 day forced libration in longitude will have twice the amplitude if the mantle is decoupled from the interior by a molten layer than it would have if the planet is a rigid body. The precise measurements necessitated by the small values of both the obliquity and the forced libration amplitude as well as similarly precise determination of C_{20} and C_{22} will be possible from either of two spacecraft, MESSENGER from the U.S. and BepiColombo from Europe, which will orbit Mercury during the next decade. More astounding, a radar technique called Radar Speckle Differential Interferometry (RSDI) (Holin, 1992) is capable of arcsec accuracy in determining both the obliquity and the forced libration amplitude from the ground, where feasibility has been demonstrated (Margot *et al.* 2002). The RSDI and spacecraft techniques will be described. Assumptions necessary for success of the experiment will be detailed, and recent numerical calculations of Mercury's spin evolution will be discussed. Some caveats will be pointed out, but as the assumptions are likely to be satisfied, there is a high probability that precise geodesy will yield the desired information about Mercury's interior.

G42C-04 1645h INVITED

Constraints on Mars Interior from k2 Love number, Moment of Inertia and Crustal Thickness

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The solar tide of Mars, measured by its potential Love number k2 (=0.153+-0.015) has been obtained from analysis of MGS radio tracking through June 2003. Atmospheric tides and inelasticity contribute to the observed signal, and we estimate that the elastic' component is k2=0.145+-0.0015. This parameter is sensitive to core size and mantle rigidity profile and indirectly on mantle composition and thermal profile. Similarly, the moment of inertia C (=0.3650+-0.0012) has been deduced from the secular precession of Mars pole of rotation, where Pathfinder and Viking tracking data are the primary data constraints. Moment of inertia is sensitive to thickness and density of the primary units: crust, mantle and core. Correlation of Mars nonspherical gravity field (primarily contrained by MGS tracking) and surface topography (fixed by MOLA data) promises to limit the thickness and density of the crustal unit overlying the mantle, with theoretical thickness estimates ranging from 50 to 100km , although any given model estimate typically limits thickness to +-10km. We shall discuss the reliability of the estimated parameters. The details related to constructing interior models (composition, density, thickness of units), from which theoretical estimates of moment and Love number are derived, also shall be discussed.

G42C-05 1700h INVITED

Estimation of Seasonally-varying CO_2 Ice Mass and Mean Atmospheric Pressure on Mars from Temporal Changes in the Gravitational Field

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The seasonal exchange of CO_2 between the atmosphere and cryosphere of Mars modifies the planetary mass distribution and results in small changes in the long-wavelength gravitational field. Over the course of the Martian year $\sim$18% of the total volatile mass will be exchanged between the atmosphere and the surface, resulting in a re-distribution of $\sim 1 \times 10^{-8}$ of the total mass of Mars. Changes in the Martian long-wavelength gravity field have been detected from orbiting spacecraft and the challenge is to relate these variations to the CO_2 cycle. In the current study we develop an analytical approach to relate gravity field changes to seasonal variations in CO_2 ice mass and to the global mean atmospheric surface pressure. We have also performed a direct recovery of temporally-varying cryospheric mass and demonstrate an equivalence to the recovery using low-degree gravity coefficients. In addition, we have estimated gravity anomalies over the poles, as yet another representation of the same phenomenon. We compare our estimates with Viking lander pressure measurements and with predictions from a General Circulation Model (GCM) simulation for a typical Mars year. This combined theoretical and observational approach provides a means of estimating the global-scale volatile mass exchange and global mean pressure on Mars on a routine basis from precise tracking of orbital spacecraft.

G42C-06 1715h

Simulation Of The Effect Of Higher Order Zonal Gravity Field Coefficients Of Mars On Jointly-Estimated Time-Varying J2, J3 And Rotation.

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Largest seasonal variations in the gravity field of Mars occur for the J2 and J3 coefficients. These coefficients were estimated recently from MGS data. It is believed that these estimates contain also additional information from the higher order coefficients. In the present study, we investigate the effect of higher order zonal gravity field coefficients on the estimation of the time-varying J2 and J3. Numerical simulations with an orbit determination computer program (GINS, provided by GRGS/CNES) are performed. Seasonal variations in the gravity field coefficients are given as input with the help of the Global Circulation Model of LMD. We study the ability to recover these values from simulated tracking data between an orbiter and the Earth. Additional radio links between the orbiter and lander(s) on the surface are also used in order to accurately constrain rotation variations.

G42C-07 1730h

Mars Polar motion excitation.

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The planet Mars is ellipsoidal and has most probably a liquid outer core. The existence of a solid inner part in the core is questionable. We compute the atmospheric excitation of the Chandler Wobble and of the possible Inner Core Wobble. The atmosphere and ice caps of Mars excite these free modes. We examine whether they are excited to an observable level in future geodetic measurements of polar motion. We have developed a theoretical approach to compute polar motion in response to the excitation of atmosphere and polar caps calculated from the output of a global circulation model.

G51A MCC: 2010 Friday 0800h

Advancing the Cutting Edge of Geodesy I: Positioning

Presiding: **Y Bock,** Scripps Institution of Oceanography**; K Larson,** University of Colorado at Boulder

G51A-01 0805h INVITED

High-Rate GPS Applications for Seismology: What Next?

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It has been demonstrated that high-rate GPS provides useful measurements of seismic waves in cases where seismic instrumentation clips. But many important questions remain to be answered. In the absense of clipping, are there any specific scientific questions that can be answered with high-rate GPS data but not with seismometers or strainmeters? At what rate should we operate GPS receivers ? What are the cost-benefit trade-offs ? Should we concentrate on real-time or post-processed high-rate GPS solutions? Examples from analysis of high-rate GPS data will be shown and discussed.