Tad W Patzek[3,4] (1-510-643-5834; patzek@patzek.berkeley.edu)

Dmitriy B Silin[4] (1-510-495-2215; DSilin@lbl.gov)

Ronald G Blom[1] (1-818-354-4681; Ronald.Blom@jpl.nasa.gov)

[1]Jet Propulsion Lab, Caltech, 4800 Oak Grove Dr., MS 300-233, Pasadena, CA 91109, United States

[2]Chevron U.S.A. Production Co., NAU SJVBU Business Unit, 15255 Lost Hills Rd., Lost Hills, CA 93249, United States

[3]Dept Civil and Environmental Engineering, UC Berkeley, 437 Davis Hall, Berkeley, CA 94720, United States

[4]Lawrence Berkeley National Lab, University of California, 1 Cyclotron Road, MS 90-1116, Berkeley, CA 94720, United States

SAR, GPS and LiDAR monitoring of the Lost Hills giant oil field in central California shows dramatic changes of subsidence over the last 15 years. Subsidence is caused by fluid withdrawal and subsequent compaction of the diatomite petroleum reservoir and in some areas has reached cumulative subsidence of 2 meters since 1989. Measurements of the surface elevation changes with semi-annual GPS surveys and SAR interferometry (using ERS-1 and ERS-2 satellite data) show subsidence rates exceeded 1 mm/day during 1995-1996 in the central part of the oil field. By 1999-2000, increased injection of water to replace the extracted fluids meant that no part of the Lost Hills field was subsiding faster than 0.5 mm/day and some areas that had extremely rapid subsidence before were slower than 0.2 mm/day. We increased the temporal resolution of the subsidence measurements for late 2002 and early 2003 by analyzing more frequent SAR acquisitions from the Radarsat-1 satellite to better understand the compaction response to changes in the oil field operations. The Radarsat-1 orbit-repeat period is 24 days but individual interferograms with short time intervals of only 24 days can have substantial errors due to atmospheric variations. Errors can be reduced by making interferograms with longer time intervals or by averaging multiple independent interferograms over a shorter interval. The Radarsat-1 satellite can image Lost Hills from up to six different tracks every 24-day cycle, potentially allowing six independent interferograms. *Part of this work was performed at the Jet Propulsion Lab, Caltech under contract with the National Aeronautics and Space Administration.

G41A-05 0900h INVITED

Inverse modeling of interbed storage parameters using land subsidence observations, Antelope Valley, California

Jörn Hoffmann[1] (+49 (8153) 28-3329; joern.hoffmann@dlr.de)

Devin L. Galloway[2] (+1 (916) 379-3737; dlgallow@usgs.gov)

Howard A. Zebker[3] (+1 (650) 723-8067; zebker@stanford.edu)

[1]German Aerospace Center (DLR), Remote Sensing Data Center, Oberpfaffenhofen, Wessling 82234, Germany

[2]United States Geological Survey, 7801 Folsom Blvd., Suite 325, Sacramento, CA 95826, United States

[3]Stanford University, Department of Geophysics, Mitchell Building, Stanford, CA 94305-2215, United States

Land subsidence above subsurface reservoirs has been observed in many locations all over the world. The observed surface displacements accompany reservoir pressure changes induced by the resource exploitation or management. In recent years satellite radar interferometry (InSAR) has increasingly complemented or replaced traditional methods for detecting and characterizing the surface displacement field above reservoirs. We have used land-subsidence observations from repeatedly surveyed benchmarks and InSAR in Antelope Valley, Mojave Desert, California to estimate interbed storage parameters controlling the subsidence in a previously calibrated regional ground-water flow and subsidence model (MODFLOW). Using the nonlinear parameter estimation program UCODE, we have estimated compaction time constants varying spatially from 3.8 to 285 years. A linear estimation of the inelastic skeletal storage coefficients yielded values between 0 and 0.09. We found that subsidence observations over long time periods were necessary to constrain the large compaction time constants in Antelope Valley. Because historical subsidence data cannot yet be provided by space-geodetic techniques such as InSAR the time-constant estimates in our model were constrained primarily by observations from benchmarks. Incorporating the resulting parameter estimates into the MODFLOW ground-water flow and subsidence model significantly improved the agreement between simulated and observed subsidence, whereas the model-simulated aquifer heads proved to be very insensitive to our modifications of the interbed storage parameters. Both the accuracy of the estimated parameters and the resulting models' ability to predict subsidence over short time periods is hampered by the fact that the simulated hydraulic heads are often not representative of the actual aquifer hydraulic heads. These errors constitute the primary limitation of the approach presented here.

G41A-06 0915h INVITED

Imaging and Analysis of Ground Surface Deformation using Tiltmeters for Reservoir Optimization

Eric Davis[1] (415-861-1097; eric.davis@pinntech.com); Chris Wright[1] (chris.wright@pinntech.com); Du Jing[1] (jing.du@pinntech.com); William Roadarmel[1] (william.roadarmel@pinntech.com); Dmitriy Astakhov[1] (dmitriy.astakhov@pinntech.com); Larry Griffin[1] (larry.griffin@pinntech.com)

[1]Pinnacle Technologies, 600 Townsend St. Suite 160W, San Francisco, CA 94103

Simultaneous injection into multiple wellbores inevitably raises questions about fluid distribution. One way to monitor both the injection and subsequent fluid withdrawal is with an array of surface tiltmeters. The tiltmeter data is used to produce a video of surface deformation, which enables quick visual assessment of the stimulated areas. The data is further analyzed when discreet events are noted. Some of these events include opening of new areas which previously received little fluid, changes in distribution caused by shut-ins and injection pressure changes, and breakthroughs into shallower zones. The geophysical inverse problem is solved using a combined volumetric and dislocation solution to quantitatively estimate the dimensions, depth, volume content and shear offset of an affected zone. The data generated by the monitoring system is used in the short term to alter injection strategies to aid production while preventing significant breakthrough into unwanted zones and in the long term to help optimize the field treatment strategy.

G41A-07 0930h

A Coupled Inversion of Pressure and Surface Displacement

D. W. Vasco[1] ((510) 486-5206; dwvasco@lbl.gov)

Kenzi Karasaki[1] (kkarasaki@lbl.gov)

kiyoshi Kishida[2] (kishida@toshi.kuciv.kyoto-u.ac,jp)

[1]Berkeley Laboratory, Earth Sciences Division/Bldg. 90 1 Cyclotron Road, Berkeley, CA 94720, United States

[2]Kyoto University, Department of Civil Engineering, Kyoto 606-8501, Japan

A coupled inversion of transient pressure observations and surface displacement measurements provides an efficient technique for estimating subsurface permeability variations. The methodology has the advantage of utilizing surface observations, which are typically much less expensive than measurements requiring boreholes. Furthermore, unlike many other geophysical observables, the relationship between surface deformation and reservoir pore fluid volume changes is relatively well understood. Our treatment enables us to partition the estimation problem into a sequence of three linear sub-problems. An application of the approach to a set of tilt and borehole pressure data from the Raymond field site in California illustrates it's efficiency and utility. The observations are associated with a well test in which fluid is withdrawn from a shallow fracture zone. During the test thirteen tiltmeters recorded the movement of the ground surface. Simultaneously, nine transducers measured pressure changes in boreholes intersecting the fracture system. We are able to image a high permeability, north trending channel located within the fracture zone. The existence and orientation of this high permeability feature is substantiated by a semi-quantitative analysis of some 4,000 transient pressure curves.

G41A-08 0945h INVITED

An efficient semi-analytical method for modeling strongly coupled diffusion and deformation processes in layered poroelastic media

Rongjiang Wang[1] (+49 (0)331 2881209; wang@gfz-potsdam.de)

Hans-Joachim Kuempel[2] (+49 (0)511 643 3496; kuempel@gga-hannover.de)

[1]GeoForschungsZentrum Potsdam, Telegrafenberg, Potsdam D-14473, Germany

[2]Leibniz Institute for Applied Geosciences, Stilleweg 2, Hannover D-30655, Germany

From poroelasticity theory we know that fluid diffusion will induce matrix deformation and vice versa. In practice, well known phenomena for such coupled processes are, for example, occurrence of seismotectonically induced groundwater fluctuations, land subsidence as a result of fluid extraction from subsurface reservoirs, production-induced surface strain near the vicinity of wells, reservoir- or injection-induced seismicity. Modeling of deformation and pore-pressure data that have been observed near the surface can help to image the dynamics and to assess the hydraulic properties of subsurface aquifers. We here present a semi-analytical Haskell propagator method to fully handle linear poroelastic problems in a multilayered half-space. Our method is a powerful tool for various reasons: (1) It is faster than traditional numerical schemes when respective discretization of the object region is chosen and solutions are sought for single locations only; (2) a problem is easily formulated, as only a set of five poroelastic parameters per layer plus the layers' thicknesses need to be specified; (3) the method is highly flexible, as forcing functions of point injection, single force (e.g., surface loading), double couple dislocation (earthquakes), etc. may be readily incorporated; (4) the so-called loss-of-precision problem of the original propagator algorithm has been fully overcome using the orthonormalization technique. The effectiveness of the new tool has been demonstrated by modeling pump-induced near-surface tilt data obtained at a test site near Sopron in western Hungary. The results show that the hydraulic diffusivity of the shallow subsurface aquifer can be assessed with an accuracy better than half an order of magnitude, if other elastic parameters and the geometry (depth and thickness) of the water-bearing formations are sufficiently known from, for example, bore-log records. Moreover, the present method can be applied to model induced seismicity based on the Coulomb failure criterion.

G41B MCC: Level 1 Thursday 0830h

Geodesy of Terrestrial Planets I Posters *(joint with P)*

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

G41B-0030 0830h POSTER

Solar Eclipses on Mars: Spatial and Temporal Patterns in the Motion of the Shadow of Phobos

Robert Comstock[1] ((858)534-8290; rcomstoc@ucsd.edu)

Bruce Bills[1,2] (bbills@ucsd.edu)

[1]UCSD/Scripps Institution of Oceanography, Institute for Geology and Planetary Physics, La Jolla, CA 92093-0225, United States

[2]NASA GSFC, Geodynamics Branch, Greenbelt, MD 20771, United States

The shadow cast by Phobos on the surface of Mars is small and moves rapidly, and can thus provide important relative position information. The size, shape, direction and speed of motion of the shadow evolve over a range of time scales determined by the orientations of Mars and Phobos orbits, and their relative orbital rates. We develop a simple geometric model for the temporal and spatial patterns of Phobos shadows on Mars, and comment on the possibility of using observations of the shadow of Phobos as a supplemental method for determining lander locations. The orbital parameters for the Mars-Phobos system are sufficiently different from the Earth-Moon system that terrestrial eclipse experience is a poor guide. The lunar orbit, with mean angular rate 13.33 deg/day, mean radius 60.2 Earth radii, and variable inclination (18-28 deg) to the equator plane, makes solar eclipses on Earth relatively rare. With an average of 2.38 eclipses per year, only a small fraction of the globe experiences a total eclipse in any given century. In contrast, the orbit of Phobos, with rapid mean motion of 1152 deg/day, small mean radius of 2.7 Mars radii, and negligible inclination of 1.1 deg, provides a favorable eclipse environment. Although the size and orbital distance of Phobos are such that total solar eclipses never occur on Mars, partial eclipses are common, with an average of 3.22 per day throughout most of each annual cycle. The Viking Lander 1 (VL1) camera system captured three Phobos eclipse events on 20, 24, 28, September 1977. On Earth, one would never see a series of eclipses at one location over such a short time scale. However, on Mars it is possible to see two eclipses in one day at a single location. A goal of the present study is to address the likelihood of observing a sequence of eclipses, similar to that observed by Viking 1, at a single site. A

substantial portion of the surface in the latitude band between -60 and 60 degrees experiences an eclipse event over the course of a Mars year, with exceptionally dense coverage at low latitudes. Since the predicted landing sites of Beagle 2, and Mars Exploration Rovers are all at lower latitudes, this study suggests ample opportunity for making Phobos shadow observations. Beyond their potential use in establishing lander location, multispectral measurements of shadow duration and intensity can also act as probes of local atmospheric conditions, and subsurface thermal properties.

G41B-0031 0830h POSTER

Mercury's Tides And Core

Tim Van Hoolst[1,2] (+32 2 3730668; tim.vanhoolst@oma.be)

[1]Royal Observatory of Belgium, Ringlaan 3, Brussels 1180, Belgium

[2]Katholieke Universiteit Leuven Institute of Astronomy, Celestijnenlaan 200B, Leuven 3001, Belgium

Mercury's solid body tides are the largest of the solar system planets. Since tides are very sensitive to the presence of a liquid core and its dimension, observation of the tides by upcoming missions to Mercury such as MESSENGER and BepiColombo holds the promise of improving our knowledge of Mercury's deep interior. We present a catalogue of Mercury tides and study the dependence of the tides on the interior structure models. For a large set of models, we calculated tidal displacements, gravity variations, and external potential variations. The models calculated differ mainly in core dimension, composition, and inner core dimension. Data on core material relevant for the pressures and temperatures in Mercury's core is used. Sulfur is considered as the main light element, and we investigate the effects of sulfur dissolving in the solid inner core. The tidal results are combined with results from gravity and libration measurements to study further constraints on the models of Mercury. We also briefly address tidal dissipation in Mercury.

G41B-0032 0830h POSTER

Monitoring Mars LOD Variations from a High Altitude Circular Equatorial Orbit: Theory and Simulation

Jean-Pierre Barriot[1] (33561332894; jean-pierre.barriot@cnes.fr)

Veronique Dehant[2] (3223730266; veroniq@oma.be)

Julien Duron[2] (julien.duron@oma.be)

[1]OMP/CNES, 14, Av. E. Belin, Toulouse 31400, France

[2]ORB, 3, Av. Circulaire, Brussels 1180, Belgium

We compute the perturbations of a high altitude circular equatorial orbit of a martian probe under the influence of an annual variation of the martian lenght of day. For this purpose, we use the first order perturbations of the newtonian equations of motion, where the small parameter is given from the hourglass model of Chao and Rubincam, which allow a simple computation of CO2 exchanges during the martian year. We are able to demonstrate that the perturbations contains two components: the first one is a sine/cosine modulation at the orbit frequency, the second one is composed of terms of the form exp(t)*sin(t), so the orbit may not stable in the long term (several martian years), with perturbations growing exponentially. We give the full theory and numbers.

G41B-0033 0830h POSTER

Determination of Variations in Ellipsoidal Shape of Mars From Paleo-shorelines

Roxanne Gratton[1] (gratton@chimie.univ-nantes.fr)

Jean-Claude Mareschal[1] (jcm@olympus.geotop.uqam.ca)

Christophe Sotin[2] (sotin@chimie.univ-nantes.fr)

[1]GEOTOP-UQAM-McGill, B.P. 8888 succursale centre-ville, Montreal, QC H3C 3P3, Canada

[2]Laboratoire de Planetologie et Geodynamique, Universite de Nantes 2, rue de la Houssiniere B.P. 92208 cedex 3, Nantes 44322, France

Following Parker (1993), three contacts traced on Viking and MOC images have been tentatively identified by Clifford and Parker (2001) as paleo-shorelines: Meridiani, Arabia, and Deuteronilus. As Head et al. (1999) did, we checked that these contacts stay along an equipotential and we found that the deviation is too important for these contacts to be paleo-shorelines unless the reference ellipsoid changed after the formation of Meridiani, the first of these contacts. For a triaxial ellipsoid, the longitudinal variation of the potential along the equator follows the variation in radius to the center of mass. Assuming that the best-fit ellipsoid of Mars changed with time, we have found the best fitting ellipsoid along the three contacts in order to deduce the time variation in equatorial flattening. For this preliminary study, we assumed that the polar flattening stayed constant. The best-fit ellipsoid for the contact Meridiani had an equatorial flattening of 1/1100. For the contact Arabia, we obtained a different value, 1/1000 for the equatorial flattening, and we believe that there had been a regression. A second variation of the equatorial flattening to 1/2544, is needed for the contact Arabia. For the contact Deuteronilus, we also obtained two best-fitting ellipsoids. For the first one, the equatorial flattening is the same as the second Arabia, 1/2544, but there was a regression. For the second one, the equatorial flattening, is 1/5000. The present value of the equatorial flattening is 1/2544. Because we can date these contacts from the age of the surface where they are observed, we can try to relate these variations of the ellipsoid shape to past tectonic activity. The reference ellipsoid, elongated at the beginning, became more circular. A tentative interpretation is that the Meridiani and Arabia contacts formed during the Noachian and the elongated ellipsoidal shape would be related to the formation of the dichotomy. The Deuteronilus contact formed later during the Hesperian when the volcanism of Tharsis dome began (Tanaka, 1986).

Clifford and Parker Icarus, 154, 40-79, 2001.
Head, J.W. et al., Science, 286, 2134-2137, 1999.
Parker, T.J., J. geophys. Res., 98(E6), 11061-11078, 1993.
Tanaka, K.L., J. geophys. Res. 91, 139-158, 1986.

G41B-0034 0830h POSTER

An Evaluation of VLBI Observations for the Precise Positioning of the NOZOMI Spacecraft

ICHIKAWA Ryuichi[1] (richi@crl.go.jp); SEKIDO Mamoru[1] (sekido@crl.go.jp); OSAKI Hiroo[1] (osaki@crl.go.jp); KOYAMA Yasuhiro[1] (koyama@crl.go.jp); KONDO Tetsuro[1] (kondo@crl.go.jp); OHNISHI Takafumi[2] (ohnishi@ssd.ssg.fujitsu.com); Yoshikawa Makoto[3] (makoto@pub.isas.ac.jp); . Nozomi Dvlbi group[4] (none)

[1]Kashima Space Research Center, Communications Research Laboratory, 893-1 Hirai, Kashima 314-8501, Japan

[2]Fujitsu Co. Ltd., Shiodome City Center, 1-5-2 Higashi Shinbashi, Tokyo 105-7123, Japan

[3]Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara 229-8510, Japan

[4]ISAS, NAO, GSI, NASDA, Gifu Univ., Hokkaido Univ., Yamaguchi Univ., and SGL/CRESTech, no address, no address none code

We performed more than 30 VLBI experiments for the NOZOMI spacecraft navigation from September 2002 until July 2003. NOZOMI, which means "Hope" in Japanese, is the Japan's first Mars probe developed and launched by the Institute of Space and Astronautical Science (ISAS). NOZOMI was originally scheduled to reach its destination in October 1999. However, NOZOMI had to be forced to make extra maneuver due to malfunction of a thruster valve during the powered earth swing-by. As a result, it was found that NOZOMI no longer had enough fuel to inject itself into its scheduled orbit on arrival at Mars. Fortunately, the ISAS mission analysis team succeeded to reschedule its flight plan to meet both fuel and observation conditions. According to the new trajectory strategy, NOZOMI's arrival at Mars is scheduled in the middle of December 2003 through two additional earth swingbys in December 2002 and June 2003. Our main concern was to determine the NOZOMI orbit just before the second earth swingby on June 19, 2003. It was significantly important to get the timing to maneuver the NOZOMI before the swingby. ISAS scientists were afraid that the range and range rate (R&RR) orbit determination might not be available because it was difficult to point the high-gain antenna mounted the spacecraft toward the earth during the period between two swingby events. So we started to support the orbit determination of the NOZOMI using differential VLBI technique since September 2002. These VLBI experiments are also aimed to establish the positioning technology for the interplanetary spacecrafts in realtime. We use nine VLBI antennas in Japan to carry out the VLBI experiments at X-band. Algonquin 46-m of the Space Geodynamics Laboratory (SGL) of CRESTech also participated in the several experiments. We equipped the state of the art "K5 VLBI system" to these stations. The K5 system is the multiple PC-based VLBI system equipped with a specific PCI-bus board on the FreeBSD and Linux operating system. The K5 system includes the original software packages which are data sampling and acquisition, real-time IP data transmission, and correlation analysis. For the purpose of analyzing the VLBI observables we are developing the specific VLBI delay model for finite distance radio source. The model is already implemented in the VLBI software package. The package will include the VLBI observation scheduling to take account of the passage of the spacecraft near the quasar line of sight and the propagation delay estimating for the ionosphere and the neutral atmosphere. We can successfully detect fringes of NOZOMI range signal for several baselines using software correlation in spite of weak and narrow-bandwidth signal. We provided 15 VLBI group delay data sets to ISAS to support the orbit determination at the end of May 2003. On the other hand, ISAS scientists have fortunately succeeded to determine the NOZOMI orbit using R&RR observables at the end of May 2003. Preliminary results demonstrate that the VLBI delay residuals are consistent with R&RR observables. However, the rms scatter between them are relatively large up to several tens nanoseconds. We are now evaluating our VLBI data sets by comparing with the R&RR results.

G41B-0035 0830h POSTER

Interior Models and Gravity Field of Jupiter's Moon Amalthea

Gudrun Weinwurm[1] (+43 1 58801 12806; gweinw@luna.tuwien.ac.at)

Robert Weber[1] (+43 1 58801 12865; rweber@luna.tuwien.ac.at)

[1]Institute of Geodesy and Geophysics, Gusshausstrasse 27-29, Vienna A-1040, Austria

Before its final plunge into Jupiter in September 2003, GALILEO made a last visit to Jupiters moon Amalthea. This final flyby of the spacecrafts successful mission occurred on November 5, 2002. In order to analyse the spacecraft data with respect to Amaltheas gravity field, interior models of the moon had to be provided. The method used for this approach is based on the numerical integration of infinitesimal volume elements, which are calculated by the scale factors of a three-axial ellipsoid (elliptic coordinates). To derive the gravity field coefficients of the body, the second method of Neumann was applied. Based on the spacecraft trajectory data provided by the Jet Propulsion Laboratory, GALILEOs velocity perturbations at closest approach could be calculated. We have derived the harmonic coefficients of Amaltheas gravity field up to degree and order six, for both homogeneous and reasonable heterogeneous cases. Based on these numbers we calculated the impact on the trajectory of GALILEO and compared it to existing Doppler data. Although no two-way Doppler-data was available during the flyby and the harmonic coefficients of the gravity field are buried in the one-way Doppler-noise, the calculated gravity field models of Amalthea can be a basis for further exploration of the Jupiter system. Furthermore, the model approach can be used for any planetary body.

G41B-0036 0830h POSTER

Mars Nutation Resonance Due To Free Inner Core Nutation

Pascale Defraigne[1] (32-2-373 02 60; p.defraigne@oma.be)

Attilio Rivoldini[1] (a.rivoldini@oma.be)

Tim Van Hoolst[1] (t.vanhoolst@oma.be)

Véronique Dehant[1] (v.dehant@oma.be)

[1]Royal Observatory of Belgium, Av Circulaire, 3, Brussels 1180, Belgium

The rotational normal modes of the planet Mars are computed using a numerical approach. We determine the associated resonances in the nutations induced by the external gravitational forcing from the Sun, Phobos and Deimos. In particular, the influence of a possible solid inner core inside a liquid core is investigated. A normal mode associated with the inner core, the Free Inner Core Nutation (FICN), is computed as well as the associated resonance effects in the nutations. For a small inner core, before the eutectic composition of the outer core is reached, the FICN effect on nutation is generally negligible. For a large inner core it can be very important, and for some nutations it can greatly decrease the resonance effect of the classical Free Core Nutation. Using future observations of Mars nutation resonances, expected from the NEtlander Ionosphere and Geodesy Experiment (NEIGE) foreseen for the mission NetLander, it will therefore be possible to get information about the inner core of Mars.

G41B-0037 0830h POSTER

A Joint Inversion Method of Electromagnetic,Geodetic and Seismological Data for the Study of Planetary Interiors

Attilio Rivoldini[1] (rivoldini@oma.be); Olivier Verhoeven[1,2] (verhoeven@oma.be); Pierre Vacher[2] (pierre.vacher@chimie.univ-nantes.fr); Veronique Dehant[1] (dehant@oma.be); Michel Menvielle[3] (michel.menvielle@cetp.ipsl.fr); Antoine Mocquet[2] (Antoine.Mocquet@chimie.univ-nantes.fr); Gal Choblet[2] (Gael.Choblet@chimie.univ-nantes.fr); Aurianne de le Court[1] (delecourt@oma.be)

[1]Royal Observatory of Belgium, 3, avenue Circulaire, Bruxelles 1180, Belgium

[2]Laboratoire de Planétologie et Géodynamique, UMR-CNRS 6112, Université de Nantes, 2, rue de la houssinière, Nantes 44322, France

[3]CETP, UMR-CNRS 8639, Observatoire de Saint-Maur, 4, avenue de Neptune, Saint-Maur-des-Fossé 94107, France

A new method is developed to determine the structure of telluric planetary interiors. It is based on the joint inversion of data from in situgeophysical experiments and laboratory measurements. We infer conditional probability densities of the parameters governingthe internal structure by stochastic inversion. This multi-parameters approach is quite generic and canbe applied to any telluric planet. We illustrate it here withsimulated data of the future Netlandermission to Mars. The simulated data come from the electromagnetic, geodetic and seismological experiments. This approach is free of any a priori assumption regarding thetemperature profile of the planetary mantle. From the inferred conditional probabilities we estimate the mineralogy and the temperature profile for the mantle as well as the sulfur weight fraction and the temperature profile for a possible liquid core.

G41B-0038 0830h POSTER

Mars Rotational Parameters from Lander-Orbiter and Lander-Earth Radio-Links

Marie Yseboodt[1] (m.yseboodt@oma.be)

Jean-Pierre Barriot[2] (Jean-Pierre.Barriot@cnes.fr)

Veronique Dehant[1] (v.dehant@oma.be)

Pascal Rosenblatt[1] (Pascal.Rosenblatt@oma.be)

[1]Royal Observatory of Belgium, 3 Av. Circulaire, Brussel 1180, Belgium

[2]Observatoire Midi-Pyrenees, UMR 5562/GRGS, 14 Av. E. Belin, Toulouse 31400, France

With an analytical formulation, we model a Martian Lander-Earth radio link, such as Viking or Pathfinder radio data, and a Martian Lander-Orbiter Radio-Link, as approximation of the future NEIGE (NEtlander Ionosphere and Geodesy Experiment) data. We construct both Doppler and Range observables. These observables have been expressed as a function of time, of the configuration parameters like stations positions or orbit elements, and of Mars' orientation parameters i.e. precession rate, nutations, length-of-day variations and polar motion. We compare the signatures of these rotational parameters on the observables. The temporal decreases of the a posteriori uncertainties on each parameter, as well as the correlations between them are also studied. The difference in the uncertainties when using the Lander-Orbiter and Lander-Earth links are mainly due to the geometry of the configuration and to the distance between the transmitter and the observer for the Doppler observables. We particularly investigate the associated uncertainties on the internal structure of Mars, like inertia moment deduced from precession rate, core and inner-core state and radius from nutations.

G41C MCC: 3005 Thursday 1020h

Signal Versus Noise in GPS Height Time Series I

Presiding: **T van Dam,** European Center for Geodynamics and Seismology**; G Blewitt,** Nevada Bureau of Mines and Geology and Seismological Laboratory

G41C-01 1020h INVITED

Error Analysis of Continuous GPS Height Time Series

Simon D. P. Williams[1] (sdwil@pol.ac.uk); Yehuda Bock[2] (ybock@ucsd.edu); Peng Fang[2] (pfang@ucsd.edu); Paul Jamason[2] (pjamason@ucsd.edu); Rosanne M. Nikolaidis[2] (niko@ucsd.edu); Linette Prawirodirdjo[2] (linette@ucsd.edu)

[1]Proudman Oceanographic Laboratory, Joseph Proudman Building 6 Brownlow Street, Liverpool L3 5DA, United Kingdom

[2]Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics,, Scripps Institution of Oceanography, La Jolla, CA 92093 0225, United States

Until recently, it was typically assumed that geodetic time series, in the absence of earthquakes, consisted of a linear trend representing crustal motion, and measurement errors which were assumed to be normal (Gaussian) and statistically uncorrelated from one another (white noise). However, many geodetic data sets have now provided evidence for signals and noise that introduce large temporal correlations into the data. One common statistical model for many types of geophysical signal may be described as a power-law process, or one with time-domain behavior that has a power-spectrum of the form $P \propto f^{\alpha}$. The spectral index, α, is typically in the range$-2 < \alpha < 0$. More than 900 continuous GPS height times series from over 400 individual sites in 9 different GPS solutions were analyzed for power-law noise content using Maximum Likelihood Estimation (MLE). The lengths of the series varied from 500 to 3722 daily position estimates (around 16 months to over 10 years). In solutions where the sites were globally distributed the noise can be best described by a combination of white noise plus flicker noise. Both noise components show latitude dependence in their amplitudes (higher at equatorial sites) together with a bias to lower values in the northern Hemisphere. In the regional solutions, where an attempt has been made to remove a spatially correlated (common-mode) signal, the noise is significantly lower. The spectral index of the power law in regional solutions is more varied than in the global solutions and probably reflects a mixture of origins such as monument instability, hydrological effects, atmospheric effects, and residual common-mode noise. A significant reduction in noise can be seen for all solutions since the first continuous GPS networks began recording in the early 1990s. Until such time that all unwanted signals in the GPS height time series can be removed, a suitable stochastic model can serve as a useful description of the time series. The stochastic noise approach allows us to account for the effect such noise has on the estimation of parameters (such as rate) and their uncertainties. Furthermore, stochastic models can provide help in the search for physical explanations of the observed signal. We examine some models of expected signals to examine their suitability as candidates for the noise in a stochastic sense. At the present it appears that certain models characterise the height time series at specific frequencies, that is, annual and its harmonics.

G41C-02 1035h INVITED

Applying Surface Load Models to GPS Coordinates: the Effects of Mass Conservation and Gravitational Consistency

Peter J Clarke[1,2] (+44 191 222 6445; Peter.Clarke@newcastle.ac.uk)

Geoffrey Blewitt[1,3] (gblewitt@unr.edu)

David A Lavallee[3] (lavallee@unr.edu)

Tonie van Dam[4] (tvd@ecgs.lu)

John M Wahr[5] (wahr@lemond.colorado.edu)

[1]School of Civil Engineering and Geosciences, University of Newcastle upon Tyne, Newcastle NE1 7RU, United Kingdom

[2]Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO 80309-0431, United States

[3]Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, Reno, NV 89557-0088, United States

[4]European Center for Geodynamics and Seismology, Rue Josy Welter, 19, Walferdange L-7256, Luxembourg

[5]Department of Physics and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309-0390, United States

Increasingly, models of surface mass loads (atmosphere, ground water, continental snow/ice, and circulation-induced ocean bottom pressure) are used either to correct geodetic time series by removing seasonal and other "noise", or for comparison with geodetic parameters related to surface mass transfer. However, models of surface loading obtained by simply combining the mass redistribution due to individual phenomena will not in general be self-consistent, in that (i) the implied global water budget will not be mass-conserving, and (ii) the modelled sea level will not be an equipotential surface of the Earth system's total gravity field. We force closure of the global water budget by allowing the "passive" ocean (unrelated to circulation effects) to change in mass. As has been previously recognised for the much larger sea-level changes that occur in glacial isostatic adjustment, this passive ocean response will not be a uniform change in non-steric ocean surface height, but must necessarily be variable so as to keep the "passive" ocean surface on an equipotential (at periods of more than a few days). We demonstrate the effect that this forcing of physical consistency has on seasonal loading models, and compare our results with recent observations from global GPS analyses.

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Tropospheric errors in GPS time series

Arthur E. Niell (1-978-692-4764; aniell@haystack.mit.edu)

MIT Haystack Observatory, Off Rte 40, Westford, MA 01886, United States

Errors related to modeling the azimuthally symmetric component of the atmosphere are reflected primarily as errors in the height coordinate and in the atmosphere zenith delay. The use of in situ information about the state of the atmosphere, for example from a global numerical weather model, will reduce the errors in these parameters that are due to atmosphere estimation by a factor of about two compared to a seasonal model for the elevation dependence of the atmosphere delay. In addition to an overall reduction in scatter, the improvements at periods from annual down to diurnal are significant. How much these improvements are realized in the observed position scatter and accuracy depends primarily on the lowest elevation for which observations are included in the analysis. The uncertainty due to the atmosphere parameterization is dependent on the distribution of observations on the sky, and increases with decreasing minimum observed elevation. To be balanced against this, the uncertainties in the height and zenith delay estimates decrease with decreasing minimum observed elevation. Furthermore, the atmosphere error is a strong function of latitude, increasing by a factor of about two from the equator to 60 degrees. At the same time the height precision is decreasing due to the loss of visible satellites in the zenith direction. In order to better assess the optimum analysis strategy I will present error budgets, for minimum elevations from 5 to 15 degrees, for the uncertainties in height both for the atmosphere models currently in use and for the anticipated use of a global Numerical Weather Model.

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Global-scale signals and systematic errors in GPS site height time series

Danan Dong (8183931827; Danan.Dong@jpl.nasa.gov)

Site height time series from global continuous GPS network provide valuable information of various geophysical processes, which cover wide range of spectrum and are no longer dominated by tectonic motion. With the improvements in GPS global network and data analysis, we are approaching the stage of using GPS site height time series to investigate post-glacial rebound, mass loading caused seasonal, inter-seasonal and intra-seasonal crustal deformation, tidal deformation, aquifer water table undulation, and tectonics caused vertical motion. The major obstacle is that the systematic errors in GPS data analysis are mixed with the signals in the site height time series. Due to the high correlation among the estimated parameters of GPS data analysis, small un-modeled systematic errors can be easily amplified into the site height solutions. Here, I will discuss on the satellite elevation angle dependent systematic errors. Then I will present the preliminary results and applications from the site height time series of the global continuous GPS network.