G41B-0037 0830h POSTER

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

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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

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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

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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

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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.

G41C-03 1050h INVITED

Tropospheric errors in GPS time series

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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.

G41C-04 1105h INVITED

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

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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.

G41C-05 1120h

Tidal Aliasing Induced Annual and Semi-annual Artefacts in Continuous GPS Height Time Series

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Coordinate time series are often derived from continuous GPS data processed as discrete 24 hour solutions. With this approach, residual semi-diurnal and diurnal crustal tide signatures are under-sampled, and aliased periodic signals in the coordinate time series arise. A secondary aliasing effect, well known from satellite altimetry studies but generally ignored in GPS analysis, arises from the repeat period of the satellite orbits being longer than the Nyquist period of the semi-diurnal and diurnal tidal signatures. The theoretical periods for these two aliasing effects are derived for the principal semi-diurnal and diurnal tidal constituents and their presence demonstrated in height time series derived from both simulated and real GPS data. It is shown that the beating of the two aliased signals invariably results in spurious time series signals with semi-annual and annual periods. Hence inadequate modeling of semi-diurnal and diurnal tidal constituents of the site deformation caused by ocean tide loading and Earth tides, can result in spurious semi-annual and annual signatures in the GPS height time series.

G41C-06 1135h

Seasonal Vertical Signals in GPS geodesy: Consequences of Using a Linear Reference Frame Model

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Geodetic positions derived from GPS observations are intrinsically relative. Generally, raw GPS solutions at a given epoch are adjusted to assign a meaningful reference to the final positions. The reference frame is, in practice, a subset of GPS sites contained in the solution along with a model that specifies secular motion of those sites. The simplest reference frame is one of a pair of stations that define a baseline. Position and motion at the other site, then, could be expressed relative to the base station which, in most cases, is assumed to be motionless, or "fixed". A more complex approach is to standardize a collection of sites. To first order, the rate of tectonic motion at many locations on the Earth's surface is constant. The real motion at a typical site is also likely to be gradual and progressive on a day-to-day timescale. Hence, a reasonable choice for a model that describes motion of the reference sites is a linear model. Adjustment of the raw GPS observations, then, may be realized by shifting the solution as a whole so that the subset of reference sites matches the positions predicted by the linear model. For extended and global networks, a seven-parameter (3 translations, 3 rotations, and a scale factor) transformation is generally utilized. Position timeseries derived from adjusted GPS observations have several characteristics that may be traced to the reference frame fitting procedure. First, alignment of daily geodetic solutions with a simple model of motion of the reference sites, such as a linear model, tacitly forces day-to-day positional changes at reference sites to be gradual and progressive, similar to the model that the solutions are being fit to. In most cases, this is desirable as much of the day-to-day fluctuation in apparent position of a GPS site is likely noise. Clearly, day-to-day fluctuations that correlate between all sites within a network is not real - this coherent jitter is removed through adjustment to the reference frame model, yielding a smoothed result. The second characteristic is that velocities calculated from the adjusted solutions are linked to the base motion imposed by the reference frame model. The final characteristic - which is not a benefit, but is a problem - is that alignment of GPS solutions with a linear reference frame model means that the resulting individual station timeseries will tend to be linear as well. This is because all common-mode differences between the raw solutions and the reference frame model are subtracted out. Seasonal patterns that deviate from linearity will be removed if are coherent over the entire network. Over 100 globally distributed GPS sites have been analyzed here using GIPSY/OASIS II in a fiducial-free reference frame. The origin of the raw station coordinates is inherently close to the center of mass of the Earth system, meaning that the vertical component of site positions is well determined in the raw solutions. Inspection of the raw coordinates reveals a network-wide seasonal pattern of motion aligned with the Earth's polar axis. This coherent motion is largely removed by applying reference frame constraints. Seasonal deformation cycles related to degree-one loading are poorly managed by typical linear reference frame constraints. Some degree-one vertical motion may be absorbed by the scale parameter in the transformation which, unfortunately, will then propagate the motion to other sites as noise. Due to imbalances in the distribution of GPS sites between hemispheres, this may have the effect of creating an apparent reduction in the amplitude of annual vertical motion in the northern hemisphere and enhanced amplitudes in the southern hemisphere.

G41C-07 1150h

Development of an in situ Antenna and Multipath Calibration System for GPS Geodesy

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Geophysical applications of the Global Positioning System (GPS) for studies such as global sea level change and glacial isostatic adjustment require very high accuracy (~1 mm/year) determinations of site velocity, especially of its vertical component. However, site-dependent errors such as antenna phase-center variations, multipath, and scattering can have a significant effect on high-precision GPS applications. Despite the many efforts devoted by investigators to the calibration of those site-dependent errors, determination of these errors has proven to be elusive, since no method has been developed to measure these effects accurately in situ. We have designed and constructed a prototype antenna and multipath calibration system (AMCS) to obtain such in situ corrections. The AMCS consists of a parabolic antenna that is relatively free from these site-dependent errors. We obtain phase corrections for these errors by forming the difference between the carrier-beat phase from the GPS antenna to be calibrated and the AMCS antenna. Preliminary "sky maps" of the antenna phase and multipath contributions show root-mean-square (RMS) phase variations that are a factor of ten or more greater than the AMCS noise system we expected. To explore the source of this noise, we acquired observations over small (few degrees) patches of the sky. From the analysis of these experiments, we conclude that the source of the phase variations is antenna and multipath errors that vary ~5 mm over small changes in satellite direction. Thus, for example, differences of 1° in elevation angle can result in several mm variations in phase. Similarly, small variations in azimuth angle can also result in significant phase variations. We have also observed day-to-day mm-level changes in the calibration. We hypothesize that these phase variations are due to changes in multipath caused by changes in the local electromagnetic environment associated with, e.g., weather.

G41C-08 1205h

Recovering Height and Geodetic Scale with GPS

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As the techniques of space geodesy - satellite laser ranging (SLR), very-long-baseline interferometry (VLBI), and the Global Positioning System (GPS) - continue to improve, much effort is being focused on applying them to refine the global reference frame in support of geophysical research. One of the more challenging quantities to pin down is the frame's "absolute scale," which is directly related to the heights of the observing sites. While the absolute scale is itself of little interest, its long-term stability is critical. Spurious variations in the scale over time would manifest as apparent variations in the size of the earth, compromising studies of sea level change, post-glacial rebound, and the like. It is generally agreed that of the three operational space geodetic techniques, VLBI is pre-eminent in both the accuracy and stability of scale determination, followed closely by SLR. The performance of GPS in determining scale is not as well understood and is the subject of considerable debate. With its broad-beam transmitting and receiving antennas GPS is subject to multipath and direction-dependent phase variations, raising doubts concerning the quality of its height and scale solutions. Opinions range from "scale with GPS is undefined" to "GPS scale accuracy approaches that of VLBI and SLR." In this presentation we step through the arguments and evidence concerning GPS scale determination and present precise new results that may help to settle the question.

G42A MCC: Level 1 Thursday 1330h

Progress in Imaging and Understanding the Surface Deformation Field Above Reservoirs II Posters *(joint with H)*

Presiding: **D W Vasco,** Berkeley Laboratory, University of California, Berkeley**; H J Kuempel,** Leibniz Institute for Applied Geosciences

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G42A-0039 1330h POSTER

Irregularities in Pump-Induced Tilt Above Shallow Aquifers

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Near surface ground tilt induced by the extraction of fluids from subsurface reservoirs has repeatedly been used to constrain reservoir parameters. In general, pump-induced tilt is found to be proportional in strength to the pore pressure gradient created by the pumping, to be a function of poroelastic rock parameters, and to depend on the geometric configuration of the tilt sensor and the productive sections of a well. Assuming radial flow, the strike of the tilt signal should point toward the productive well. However, inversion of near surface tilt can be hampered through irregularities in the pump-induced signal and suffer from insufficient knowledge of the influence of heterogeneities in the subsoil, either within or above the reservoir. We can learn more about the impact of such heterogeneities and reduce ambiguities by analyzing case studies. New observational data from 3 test sites in Germany confirm that a variety of causes can produce irregularities in pump-induced surface deformation, namely: (1) The strike of a tilt signal can considerably deviate from the direction toward the active well. A reason could be that the steepest effective pore pressure gradient builds up in another than radial direction (thereby generating anisotropic fluid flow). Accordingly, tilt hodographs for a complete pump cycle may be elliptic rather than follow a line. (2) The normal rule of how the signal strength depends on the horizontal and the vertical distance may be violated. Structural heterogeneities in the subsurface are the most likely cause for this behaviour. (3) Recovery of the induced tilt signal following the cessation of pumping can be incomplete. This could indicate a non-reversible compaction possibly due to overexploitation of a reservoir. (4) A transient sign reversal of ground tilt may occur during the build-up phase of the signal. This feature could be an analogue to the so-called Noordbergum effect occasionally seen in the response of well levels at locations aside from the pumped well. We conclude that near surface deformation in the vicinity of pumped wells bears a wealth of information that may be useful to constrain the conditions of fluid flow at depth, and that there is often a need for model calculations to fully understand the involved phenomena.

G42A-0040 1330h POSTER

InSAR Observed Surface Deformation at the Buckman Well Field, New Mexico

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