MARS GRAVITY AND CLIMATE

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Introduction: Sufficiently accurate measurements of seasonal variations in Mars gravity could significantly contribute to a better understanding of the seasonal climate cycle. We compare measurement capabilities of 3 current geodetic techniques (single satellite Doppler, satellite-to-satellite range rate, and gradiometry) with expected climate signals, as output from a Mars climate model.

It appears that the best prospect for useful constraints on the Mars climate system is provided by a combination of Ka-band Doppler tracking and gravity gradiometry.

Background Information: Mars climate models are currently constrained mainly by Viking Lander surface atmospheric pressure measurements [1]. The observed seasonal pressure cycles at these two locations can be simulated very well by a simple 1-D surface thermal balance model [2], when its 6 free parameters (separate values for albedo and emissivity for each polar cap, and a soil thermal inertia for each hemisphere) are properly chosen. However, the preferred values for albedo and emissivity are quite different from those obtained via optical remote sensing. It thus appears that the 1-D climate model yields aliased estimates of these parameters.

If we had sufficiently accurate gravity measurements, it would be equivalent to a global grid of effective Viking Lander pressure measurements, with the number of grid points related to the spatial resolution of the gravity measurements. For example, if the seasonal variations were seen in a full N-th degree and order gravity model, that would comprise $M = (N+1)^2 - 4$ separate time series (M = 437 for N = 20), and would dramatically decrease the aliasing of thermal parameters in the climate models.

Accuracy Requirements: Our criterion is that the gravity measurements must not only detect climate-driven mass change, at some specified spatial and temporal resolution, but should also be able to sense changes in that pattern due to variations in the control parameters. In that way, the gravity measurements will actually be able to constrain the parameters in the climate model.

We use the climate model MarsWRF [3]. There are 4 control parameters: emissivity and albedo of surface frost, with separate values in northern and southern hemispheres. For a given set of these 4 control parameters, the model delivers values of surface frost mass and atmospheric column mass at each point of a 5° × 5° grid, at 10 day time steps, for one Mars year. We run the model for 2 Mars years, and use the values for the second year. We then compute the spatial pattern of gravitational potential associated with this mass distribution, and express that pattern in a spherical harmonic series.

Compare techniques: We consider three different approaches to measuring the gravitational field of Mars, from a satellite (or pair of satellites) in orbit about Mars. Each of these measures some aspect of the gravitational potential field in which the satellite is flying.

Doppler tracking is the usual approach, for measuring planetary gravity fields, and the only one of the three which has been deployed at Mars. It uses the Doppler shift in a microwave signal transmitted from the spacecraft to an Earth-based tracking station, to measure the line-of-sight component of velocity. Velocity is the time integral of acceleration, and acceleration is given by the gradient of the potential.

Satellite-to-satellite tracking involves a pair of co-orbiting satellites, and measures the range and/or range-rate between them. GRACE is a joint NASA-DLR gravity mission operating on Earth in this mode [4] and GRAIL is a similar NASA mission orbiting the Moon.

Gravity gradiometry uses pairs of aligned accelerometers, on each of three orthogonal axes, to measure the full tensor of second partial derivatives of the potential. GOCE [5] is an ESA gravity gradiometer mission currently operating on Earth orbit.

Attainable Accuracy: In each of these cases, the full analysis of data and error spectra would involve detailed simulations of measurements and spacecraft trajectories. However, we can get a good approximate answer from a 2-D simulation. The gravitational potential, at position p ={r, ϕ}, is expressed as a harmonic series

$$\Phi[r,\phi] = \frac{\mu}{r}\sum_{m=0}^{\infty}\left(\frac{R}{r}\right)^m (c_m \cos[m\,\phi] + s_m \sin[m\,\phi])$$

where μ = GM is the monopole moment, R is planetary mean radius, r is radial distance, and ϕ is azimuthal angle. If we denote the satellite position vector by p, then the gravitational acceleration is given by the gradient of the potential $\ddot{p} = \nabla\Phi$, and the gravity gradient is just $\Gamma = \nabla\nabla\Phi$.

For Doppler tracking, the recovered estimates have errors given by

$$\sigma_{dop}[\{c,s\}] = \left[\frac{\varepsilon}{\sqrt{N}}\left(\frac{n\,r^2}{\mu}\right)\right]\left(\frac{r}{R}\right)^m \frac{2m}{\sqrt{1+2m+2m^2}}$$

where ε is the measurement error, N is the number of measurements, and the other parameters were defined above, in terms of the gravitational potential.

The satellite-to-satellite range-rate measurements have corresponding errors

$$\sigma_{s2s}[\{c,s\}] = \left[\frac{\varepsilon}{\sqrt{N}}\left(\frac{n\,r^2}{\mu}\right)\right]\left(\frac{r}{R}\right)^m \sqrt{\frac{1}{(1-cos[2\,m\,\delta f])}}$$

where most of the parameters are the same as above, and 2 δf is the angular separation between the pair of co-orbiting satellites. For the gravity gradiometer, the error spectrum is

$$\sigma_{grad}[\{c,s\}] = \left[\frac{\varepsilon}{\sqrt{N}}\left(\frac{r^3}{\mu}\right)\right]\left(\frac{r}{R}\right)^m \sqrt{\frac{2}{20\,m+12\,m^2+3\,m^3}}$$

Measurement errors for Doppler tracking data are typically 0.1 mm/s, over a 60 s integration time, at X-band (8-12 GHz) and 0.01 mm/s at Ka-band (27-40 GHz). The accuracy of a super-conducting gravity gradiometer that was proposed 15 years ago for Earth gravity investigations [6,7] was estimated to be 10^{-3} E/$\sqrt{Hz}$, where the standard unit of gravity gradiometry is $E = E\ddot{o}tv\ddot{o}s = 10^{-9}\,s^{-2}$.

An improved design appears capable of better performance by a factor of 100 [8]. The cases shown in figure 1 assume the nominal value, and a 10-fold improvement.

Figure 1 compares present knowledge of the Mars gravity field, with the expected climate signal and estimates which could be obtained in a 30 day observation period, from a 250 km altitude orbit. Using Ka-band Doppler tracking, to constrain the orbit, and lowest degree gravity, augmented by a gravity gradiometer appears to be the best option.

References: **[1]** Hess, S.L. et al. (1980), GRL, 7, 197-200. **[2]** Wood. SE. & D.A. Paige (1992), JGR, 98, 10,963-10,971. **[3]** Richardson, M.I. et al. (2007), JGR, 112, E09001. **[4]** Tapley, B.D. et al. (2004), GRL, 31, L09607. **[5]** Drinkwater, M.R. et al. (2003), Space Sci. Rev., 108 419-432. **[6]** Canavan, E.R. et al. (1996), Cryogenics, 36, 795-804. **[7]** Shirron, P.J. et al. (1996), Cryogenics, 36, 805-813. **[8]** Shirron, P.J. et al. (2010), AGU Fall meeting