

**TAKING THE PULSE OF MARS WITH THE INSIGHT VBB SEISMOMETER.** L. Pou<sup>1</sup>, F. Nimmo<sup>2</sup>, P. Lognonné<sup>3</sup>, D. Mimoun<sup>1</sup>, R. F. Garcia<sup>1</sup>. <sup>1</sup>DEOS/SSPA, ISAE-Supaero, Toulouse, France (l.pou@isae.fr) <sup>2</sup>Dept. Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, USA <sup>3</sup>IPGP, Paris, France

**Introduction:** Mars has a pulse; the Sun and the Martian moons, Phobos and Deimos all raise tides that cause periodic variations in the planet's shape and gravity field. The amplitude and phase of this tidal response provide information about the interior structure of Mars, notably on the state and size of its core [1-4]. One goal of the InSight mission is therefore to use the VBB seismometer [5] as a gravimeter to measure Mars's response to tides raised by Phobos [4-5].

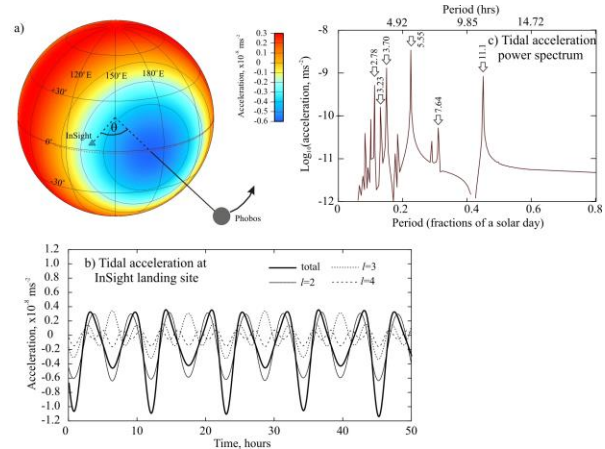
**What tidal signals are expected?** Because Phobos is so close to Mars, degree-2, -3 -4 and further tides are all present [1-3,7-8], and will be sensitive to the elastic properties of different depth ranges within Mars. Solar tides are larger but have the same period as major noise sources (e.g. diurnal pressure and temperature variations [3-4,9]). In contrast, Phobos tides, while smaller, occupy a range of frequencies separate from these major noise peaks.

The magnitude of the change in gravity due to the Phobos tides is given by [3]

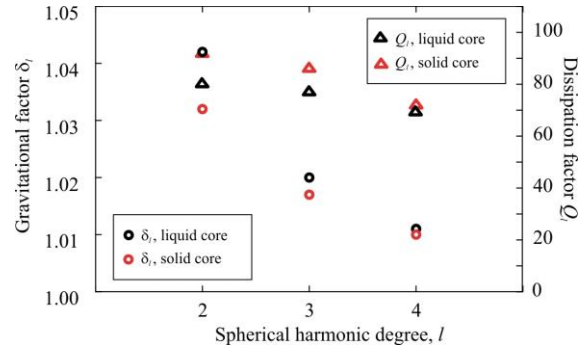
$$\Delta g_l = -\delta_l \left[ g_0 l \frac{m}{M} \left( \frac{R}{r} \right)^{l+1} \right] \quad (1)$$

where  $l$  is the spherical harmonic degree,  $g_0$  is the surface acceleration,  $m$  and  $M$  are the mass of Phobos and Mars,  $R$  is the radius of Mars and  $r$  the distance to Phobos. The acceleration amplitude at degrees 2, 3 and 4 is  $5.85$ ,  $3.18$  and  $1.53 \times 10^{-9} \text{ ms}^{-2}$ , respectively. The tidal response of Mars is described by the gravitational factor  $\delta_l$ . Fig. 1 shows the predicted acceleration experienced at the InSight site as a function of time. The bold line shows the total acceleration, while the dashed line shows the individual contributions from  $l = 2, 3$  and  $4$ . As expected, the higher-degree terms are smaller in amplitude and also have shorter periods.

**What do tides tell us?** Eq. (1) shows that a measurement by InSight of the tidal acceleration allows the gravimetric factors  $\delta_l$  to be derived. The amplitude of these factors mostly constrains the rigidity and core size [3], while the phase lags (parameterized by  $Q_l$ ) depend on the mantle attenuation and are sensitive to its temperature [6]. Fig 2 plots  $\delta_l$  and  $Q_l$  for Mars models with and without a liquid core. In order to distinguish between likely models,  $\delta_l$  will need to be measured with an uncertainty of 1% or better [1-4]. The effect on  $Q_l$  of the core state is different to that of varying the mantle temperature; a measurement of  $Q_3$  and/or  $Q_4$  to a precision of about 10% would allow these two effects to be disentangled.



**Figure 1:** a) Colours represent instantaneous  $l=2$  tidal acceleration from Phobos. b) Time series of predicted Phobos tidal acceleration. Bold line is total; thin lines are individual spherical harmonic components. c) Power spectrum of acceleration using 180 days of synthetic data. Individual peaks are marked with period in hours.



**Figure 2:** Model Martian tidal response parameters illustrating the difference between a solid and liquid core, calculated using the method of [6]. Each spherical harmonic term has a different forcing frequency (see Fig. 1).

**What are the noise sources?** The two most important noise sources are thermal noise (temperature-induced changes in geometric properties of the VBB) and pressure noise (deformation of the Martian surface due to the pressure). At diurnal frequencies, the expected contributions are  $8 \times 10^{-4}$  and  $4 \times 10^{-6} \text{ ms}^{-2}$ , compared with the full tidal signal of  $6 \times 10^{-9} \text{ ms}^{-2}$  and with the VBB temperature sensitivity [4]. Thus, a combination of noise removal and filtering will be required.

**How can the tidal signal be extracted?** We may write the signal recorded by InSight as

$$g_{\text{obs}}(t) = g_{\text{temp}}(t) + g_{\text{press}}(t) + g_{\text{tidal}}(t) + g_{\text{others}}(t)$$

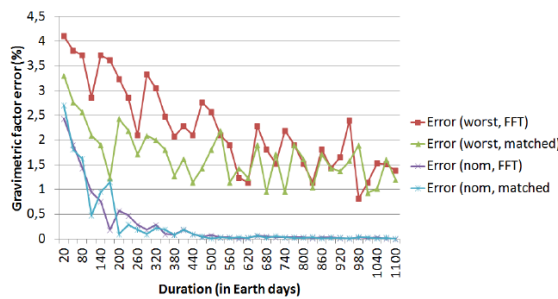
where obs, temp, press and tidal refer to the recorded, temperature, pressure and tidal contributions; others

indicate either other noises such as magnetic noise which are negligible at the tidal frequencies compared to the first three signals. The temperature near the VBB is measured by the SCIT sensor [5]. To retrieve the VBB sensitivity to changes in temperature  $\alpha$ , we use a matched filter [11] to maximize the correlation between the residual:

$$g_{\text{resid}}(t) = g_{\text{obs}}(t) - \alpha T(t - \Delta t)$$

and the measured pressure, where  $\Delta t$  denotes the time-lag between the SCIT sensor and the VBB, as pressure noise is the most important contribution after thermal noise. This residual can then be correlated against the measured pressure record [4,12] to subtract the pressure contribution  $g_{\text{press}}$ . The desired tidal signal  $g_{\text{tidal}}$  can then be retrieved by stacking or matched filtering.

Fig. 3 plots the result of end-to-end simulations of these processing steps, showing the uncertainty in the gravitational factor  $\delta_2$  as a function of time. It can be seen that in the worst-case scenario the error is less than 2.5% after two Martian years, and in the nominal case, the error is less than 0.1%.

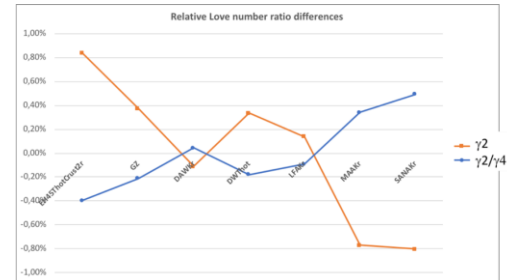


**Figure 3:** Error on the recovered gravitational factor  $\delta_2$  as a function of time, depending on the method used (FFT stacking or matched filtering) and either worst-case or nominal case on the temperature sensor self noise [1]. For higher degrees, nominal errors are below 1%.

**Absolute calibration:** Using eq. (1) to link the measured gravity variations with  $\delta_i$ , knowledge of the absolute gain of SEIS is required. To do so, an absolute calibration will be done in-situ [1], for the first time on Mars, by altering the tilt of the SEIS assembly using leveling actuators; by comparing the response of the VBB and SP instruments, a relative calibration is achieved. If its result is similar to calibrations done on Earth, we can assume that no significant changes occurred and that the terrestrial transfer function can be used for the VBB. The modeled error on the VBB gain is 0.4% [1] with respect to Earth reference instruments. To this error budget must be added errors on the ephemerides of Phobos (around 0.5%), and errors on the terrestrial VBB transfer function.

**Relative gravitational factors ratio:** To avoid the need for an active calibration, an alternative method [5] is to determine  $\delta_i$  or  $Q_i$  at two different degrees (eq

1) and taking the ratio (e.g.  $\delta_4/\delta_2$ ). Since these both depend in the same way on the VBB gain, the ratio of measurement is independent of gain uncertainty and Phobos mass and reduces errors from Phobos ephemerides. Fig. 4 shows the values expected of the gravitational factor  $\delta_2$  and the ratio  $\delta_4/\delta_2$  for several Martian models [5].



**Figure 4:** Deviation of the Phobos gravitational factor  $l=2$  (in red) and of the ratio between the  $l=2$  and  $l=4$  factors in blue. The second one varies by about  $\pm 0.4\%$  for the range of a-priori models but will not depend on an absolute calibration of SEIS.

**Conclusion:** Because of the proximity of Phobos, it is possible for the InSight VBB seismometer to record gravity variations due to Phobos tides, which can be used to constrain the interior structure of Mars. Using matched filtering, the tidal signal can be extracted and linked to the gravitational factor. Then, either using an absolute approach on single-degree gravitational factors or a relative approach using ratio of gravitational factors with different degrees, it is possible to discriminate possible Martian models. Using *a priori* models from [11,12], it is expected for the nominal duration of InSight to constrain the state of the core and its size better than  $\pm 120$  km.

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