Supplementary Information 2: Detection, analysis and removal of glitches from InSight's seismic data from Mars

Mathematical description of the glitch plus precursor origins

Let us consider a general geometry such as depicted in Figure 8b where a cross section through a VBB sensor perpendicular to its hinge is graphed. In this figure, the SEIS sensor assembly is rotated around the tip of leg A by a small angle α such that the tip of leg B is raised by $d \cdot \alpha$, with d being the distance between the tips of the legs. The sensitive axis of the VBB accelerometer, denoted with the unit vector $\hat{\sigma}$, is inclined relative to the horizontal by the angle δ which is close to -29°, depending on the VBB sensor.

The force of gravity acting on the proof mass M and which the suspension spring has to counterbalance is:

$$F_o = g \cdot M \cdot \sin(\delta), \tag{1}$$

where $g = 3.71\mathrm{m/s}^2$ is the surface gravity on Mars. After the tilting of SEIS by the angle α, the projection of $\vec{g}$ onto the sensitive axes changes and it follows:

$$F = g \cdot M \cdot \sin(\delta + \alpha). \tag{2}$$

The change in acceleration $\ddot{u}$ produced by the tilting thus is:

$$\frac{F - F_o}{M} = \ddot{u} = g\alpha \cos(\delta). \tag{3}$$

Since the rotation axis does not go through the center of gravity P of the proof mass M, the rotation leads also to a displacement of the proof mass. In our case this displacement, y, is a small arc segment of a circle with radius $r = \overline{AP}$ around the tip of leg A: $y = r \cdot \alpha$. The accelerometer only senses the projection of this displacement onto its sensitive direction. If we define the unit vector $\hat{r}$ as:

$$\hat{r} = \frac{\vec{AP}}{|\overline{AP}|}, \tag{4}$$

the sensed displacement then becomes:

$$u = r \cdot \alpha \cdot |\hat{r} \times \hat{\sigma}|. \tag{5}$$

What is the time history of this tilt and the simultaneous displacement? As we shall see, the data can be very well modeled by assuming that the time dependence follows a Heavyside function, that is the tilt and the displacements occur over a time interval much shorter than can be resolved with the given sampling interval. In the analyzed glitches we see no indication for a slowly progressing tilt.

Now we have to account for the fact that inertial accelerometers like the VBB and SP seismometers in the SEIS package have a frequency dependent sensitivity to ground motion. This is described by the impulse response $T(t)$. In the time domain the output of the seismometer then becomes the convolution of the input convolved with the impulse response where the input can be the ground displacement, ground velocity or ground acceleration. The seismometer response to a Dirac impulse

Corresponding author: John-Robert Scholz, `scholz@mps.mpg.de`

in displacement, velocity or acceleration are denoted $T_{DIS}(t)$, $T_{VEL}(t)$ and $T_{ACC}(t)$, respectively. They are related by:

$$T_{DIS}(t) = \dot{T}_{VEL}(t) = \ddot{T}_{ACC}(t). \tag{6}$$

The summed output U from the acceleration step due to the tilting at time t_o and the associated displacement step then becomes:

$$U(t) = g\alpha\cos(\delta) \cdot H(t - t_o) * T_{ACC}(t) + r \cdot \alpha \cdot |\hat{r} \times \hat{\sigma}| \cdot H(t - t_o) * T_{DIS}(t). \tag{7}$$

Since the impulse responses due to ground displacement is the second time derivative of the impulse response due to ground accelerations, we anticipate that the acceleration step produces a low-frequency response while the displacement step should be dominated by high frequencies. This is exactly what the Figures 1 and 6 show. The step in acceleration leads to the glitch while the step in displacement leads to the high-frequency precursor.

When modeling the glitches and their precursors, we obtain the time of the occurrence of the glitch, t_o, as well as the acceleration and displacement steps. From the acceleration $\ddot{u}$ step we can infer the tilt angle α based on Equation (3). What is not possible is to infer the location of the rotation axis given the observed step in displacement, u, and the rotation angle α. Only if we assume that $\hat{r}$ and $\hat{\sigma}$ are at right angles can we infer an effective distance $r_{eff} = u/\alpha$ between rotation axis and the proof mass.

To see if the mathematical simplifications are justified we plug in numbers for the glitch in figure 6 (see also table 2 in main paper): the step in acceleration is 259 nm/s^2. The inferred tilt of SEIS which is responsible for that glitch is then:

$$\alpha = \frac{\ddot{u}}{g \cdot \cos(\delta)} = \frac{259\,\mathrm{nm/s}^2}{3.71\,\mathrm{m/s}^2 \cdot \cos(29.3°)} \simeq 80.0\,\mathrm{nrad}. \tag{8}$$

So indeed, these are tiny tilt angles. The displacement obtained from modeling the precursor of this glitch is $u = 3$nm . The effective distance r_{eff} of the rotation axis away from the center of gravity of the proof mass is then:

$$r_{eff} = \frac{u}{\alpha} = \frac{3\,\mathrm{nm}}{80\,\mathrm{nrad}} = 3.7\,\mathrm{cm}. \tag{9}$$

In summary, we have shown that an accelerometer which gets rotated around a horizontal axis that does not go through the center of gravity of the proof mass senses two signals: the response to the tilt and the response to the resulting small displacement. While the former shows up in the data as the low frequency glitch, the latter leads to the high-frequency signal precursors.