

# Extramartian forcing of Mars seismicity at Rieger periods

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Studies of the InSight mission seismic data show preference to higher frequencies, localization (to the Cerberus Fossae region), and annual variation — the features uncharacteristic of earthquakes or moonquakes but typical of a resonator locked to an external forcer. I here report results from spectral analyses of InSight B- and C-quality marsquakes occurrences. The Rieger period  $P_{\text{Rg}}=154$  days, as the only 99%-significant spectral peak in the 1–6 months band, indeed dominates this (most energetic) band and is characterized by a very high ( $\gg 12$ ) fidelity  $\Phi=2.8 \cdot 10^6$ .  $P_{\text{Rg}}$  is currently one of the commonly reported periodicities in our Solar system, observed in the interplanetary magnetic field and most heliophysics data types during solar maxima. The modular Rieger Type Periodicities:  $\frac{1}{2}P_{\text{Rg}}$  and  $\frac{1}{3}P_{\text{Rg}}$ , are found also dominating Martian seismicity, at 89%–67% lowered significance levels but with  $\Phi \gg 12$  as well. Therefore, a primary underlying process drives both heliophysics and areophysics, causing the sampled tidal-resonant response. Since  $P_{\text{Rg}}$  is discernable in post-1953 solar activity only (solar cycles 19–24), Mars is tectonically inactive. This observation of the temporary Rieger-forcing extending to Mars indicates an emerging or alternating strong magnetic field, possibly Jovian.

*Keywords— Mars seismicity; tidal forcing; resonant seismogenesis; Mars tectonics; Jupiter magnetic field.*

## 1. Background and Motivation

Seismic data collected *in situ* reveal fundamental physical properties of a heavenly body. After the failure of Viking 2 lander to fully deploy its seismometer in 1976 (Lorenz et al., 2017), the second attempt to learn significantly about the main physical properties of Mars came about with the InSight mission (*Interior Exploration using Seismic Investigations, Geodesy and Heat Transport*) that landed in late 2018.

Preliminary analyses of InSight 2019-2020 seismic data revealed that the vast majority of recorded events are of high-frequency energy, exhibit uneven spatial distribution, and occur unusually remotely from the lander. At the same time, the events rate shows annual variation, unlike in earthquakes. Also, marsquakes overall exhibit no discernable seismic phase arrivals and are a highly localized phenomenon. Thus most marsquakes originate 1800 km away from the lander, at the sunken Cerberus Fossae plateau — one of the youngest geological structures on Mars possibly formed from subsidence or extensional faulting. Marsquakes themselves differ from earthquakes in many ways: they are much smaller in terms of released seismic energy, the strongest being the event recorded at teleseismic distances with a magnitude of  $\sim 3.6$ . Both local and the background seismic noise on Mars are much lower than on Earth, without the constant tremor produced by mechanical resonances. (Ceylan et al., 2021; van Driel et al., 2021)

In what follows, I use the InSight seismic data to spectrally examine the band of highest areophysical energies to determine if any external forcing contributes to the peculiarities of Martian seismicity.

## 2. Data and Methods

To look into possible external drivers of the Martian planetary dynamics, I spectrally analyze the Marsquakes Catalog by van Driel et al. (2021). As cataloged for the 2019-2020 time interval, the corrected InSight data reveal Martian planetary dynamics primarily characterized by temporally clustered rupturing and an annual (orbitally induced) variation in events frequency, Figure 1. Given the highly localized spatial clustering of the events described above, such arrangement indicates an external planetary forcing with a lock to a dominant systematic forcer active during the InSight lander's sampling of the rupturing process.

To analyze the Marsquakes Catalog, I apply the Gauss–Vaníček method of spectral analysis (GVSA) by Vaníček (1969, 1971). GVSA is the rigorous method for computing spectra by way of least squares, has many advantages over the Fourier class of spectral analysis techniques in analyzing sparse natural data of long spans (Press et al., 2007; Taylor, 1972), and has proven itself by providing absolute extraction accuracy in analyzing even extremely gapped records of data (Omerbashich, 2006, 2007). Subsequently, the method went through simplifications into non-rigorous (strictly non-least-squares) formats, such as the Lomb-Scargle technique. GVSA provides total (absolute) accuracy in extracting periods from natural data sets — to the prescribed accuracy of analyzed data themselves (Omerbashich, 2021). Fed raw data, the GVSA outputs spectral peaks with magnitudes in variance percentages (var%) against linear background noise levels. This type of processing enables relative spectral computations, whose results for physical systems are then directly energy-stratified, enabling direct separation of resonance forcers from respective harmonics and any other systematic signal contents. Here, input data are used in their raw form, i.e., without preprocessing (padding, filtering, windowing, tapering, etc.) or post-processing used by some to enhance spectra. Declared accuracy on detected spectral peaks is  $\pm 1'$ .

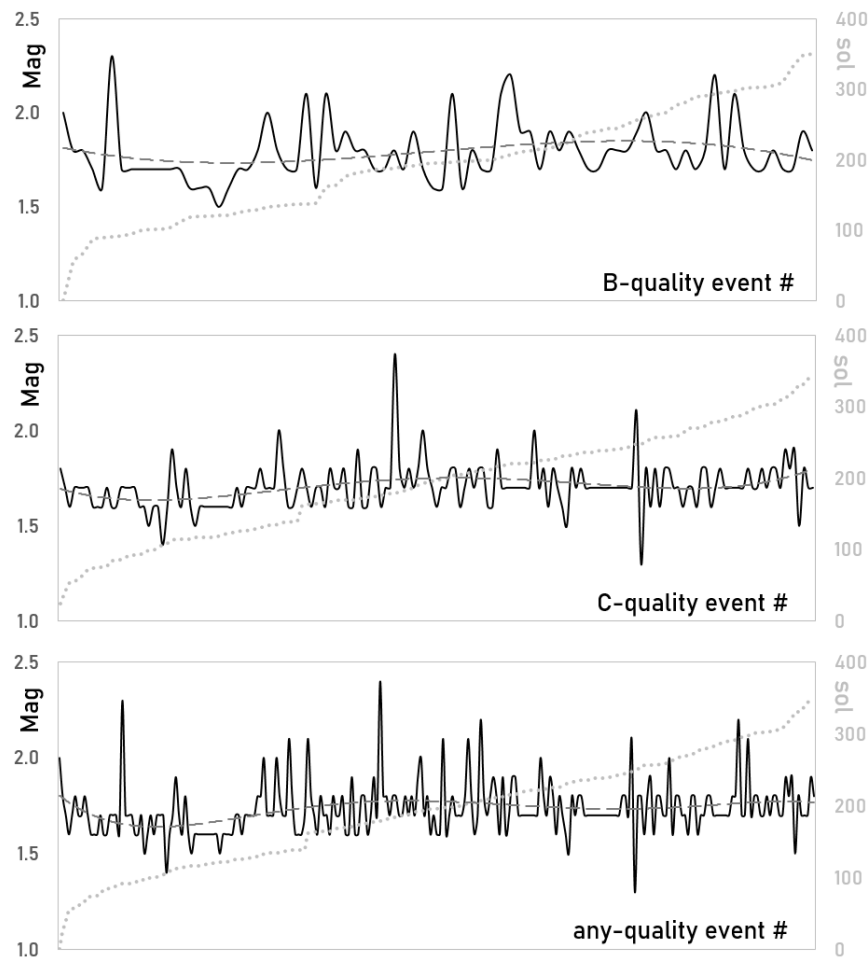


Figure 1. Marsquakes in seismic magnitudes (solid lines) v. occurrence times (dotted lines), with flattening tendency indicating temporal clustering of events. A comparison of B-quality (top panel), C-quality (mid-panel), and combined-quality events (bottom panel) suggests that the InSight record retains event frequency faithfully irrespective of data quality. This conclusion is further supported by respective polynomial trends (dashed lines), constantly indicating an orbitally induced variation in events rate. Data from van Driel et al. (2021). Note that, while spectral computations in the present study relied on the Coordinated Universal Time (UTC), the same data in Local Mean Solar Time (LMST) produce the same results.

### 3. Results and Discussion

Spectral analysis of the Marsquakes Catalog has revealed externally forced dynamics of Mars seismicity, Table 1 & Figure 2. The longest detected periodicity is 154.48-days at 4.8 var% and with a staggering statistical fidelity of  $\phi = 2900000$ , which confirms conclusively that the external forcing is dominant in Mars dynamics. Other significant periods are 42.07-days at 2.5 var% with 95% significance and again very high  $\phi = 210000$ , then 54.51-days at 2.1 var% with 89% confidence and very high  $\phi = 360000$ , and 73.87-days at 1.5 var% with 67% significance and very high  $\phi = 660000$ .

Period	Significance level	T [s]	T [days]	$T_{\text{solar}}$ [days]	$\Delta T$ [%]	$\Phi$	Mag. [var%]	Power [dB]
$P_{\text{Rg}}$	99% (3.80 var%)	13347464	154.48454	154	0.3	$2.9 \cdot 10^6$	4.8	-12.97447
$1/2 \cdot P_{\text{Rg}}$	67% (0.93 var%)	6383093	73.87839	78	5.3	$6.6 \cdot 10^5$	1.5	-18.09301
$1/3 \cdot P_{\text{Rg}}$	89% (1.84 var%)	4709442	54.50743	51	6.9	$3.6 \cdot 10^5$	2.1	-16.67086
$3/11 \cdot P_{\text{Rg}}$	95% (2.49 var%)	3635107	42.07300		0.1	$2.1 \cdot 10^5$	2.5	-15.91000

Table 1. Results of the GV spectral analysis, Figure 2, of the Marsquakes Catalog, Figure 1. The previously reported  $P_{\text{Rg}}$ ,  $1/2 \cdot P_{\text{Rg}}$ , and  $1/3 \cdot P_{\text{Rg}}$ , were matched, while the previously reported  $5/6 \cdot P_{\text{Rg}}$  and  $2/3 \cdot P_{\text{Rg}}$  periods were absorbed by  $P_{\text{Rg}}$ . Note degeneration of the  $1/3 \cdot P_{\text{Rg}}$  within the Mars vicinity into a  $3/11 \cdot P_{\text{Rg}}$  split. Note also that the above-stated matching ( $\Delta T$ ) to previously reported such periods  $T_{\text{solar}}$  is the upper limit (the worse) of such matchings, while  $1/2 \cdot P_{\text{Rg}}$  and  $1/3 \cdot P_{\text{Rg}}$  previously were also reported as in the present study, e.g., by Özgüç and Ataç (1994).

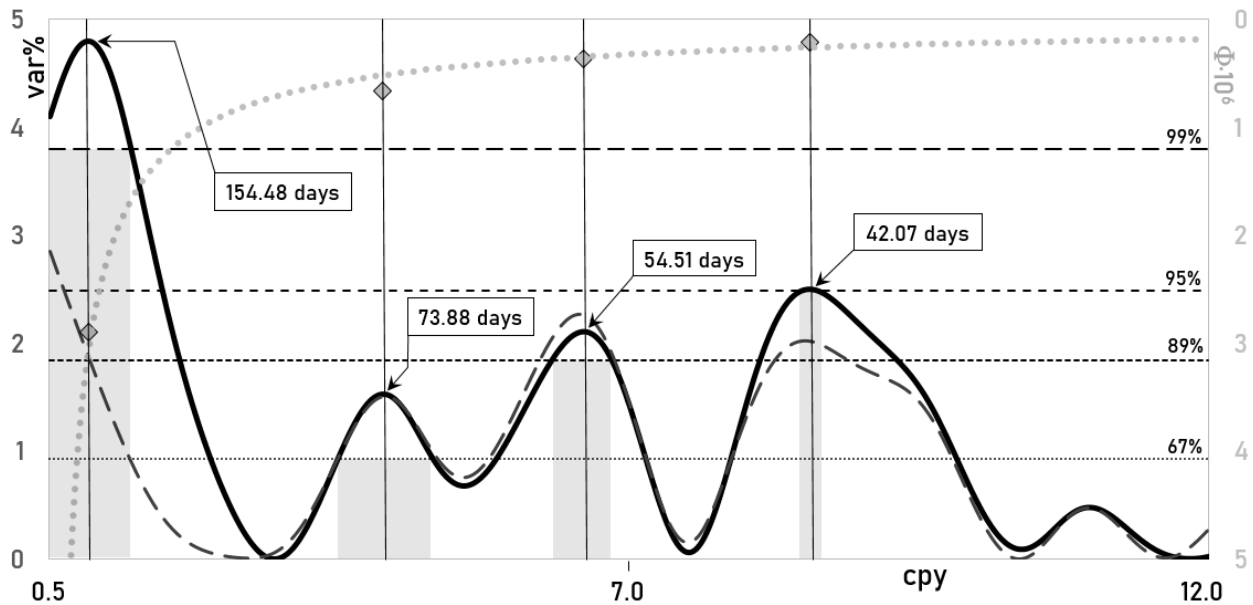


Figure 2. GV spectrum (solid curve) of the Marsquakes Catalog by van Driel et al. (2021) in the 1–6 months band of strongest planetary energies. The B-C combined-quality time series turned out sufficient for extraction of dominant forcing. Thus the Rieger period  $P_{\text{Rg}} = 154.48$  days, was returned as the system driver, since it absorbed all power at the 99%-significance level and exhibits the highest statistical fidelity found in this study, of  $\phi = 2900000$ . At the same time, the Rieger-type harmonics dominate the record across lower significance levels but with a  $\phi \gg 12$  as well, Table 1, where a fidelity of 12 and higher is considered to reflect a genuine physical process (Omerbashich, 2006). Note clustering on the  $1/3 \cdot P_{\text{Rg}}$  spectral peak. The B- and C-quality marsquakes series separately were insufficient to return spectra with any significant periodicity, so that combined B-C time series was used, which is justified by a consistent retention of the events rates regardless of the data quality level, Figure 1. The underlying spectrum (dashed curve), of the same data but with  $P_{\text{Rg}}$  mathematically suppressed (Wells et al., 1985), indicates neither additional forcing dynamics nor any areophysical systematic processes. Values of statistical fidelity per spectral peak plotted with the power trend, on the secondary axis (gray axis). The width of gray boxes represent power-absorption capacity of a spectral peak at the respective significance level.

The Solar system often exhibits different periodicities in electromagnetic radiation and energetic particle events, ranging from the ~11-year sunspot cycle to the 27-day rotational period (Chowdhury et al., 2008; Chowdhury et al., 2016), and including various mid-range periods (Bai, 2003). During solar cycle 21, Rieger et al. (1984) found the dominant (longest) such quasi-period,  $P_{\text{Rg}} = \sim 154$  days, in 139  $\gamma$ -ray and >500 soft X-ray flares recorded by the Gamma-Ray Spectrometer (GRS) aboard the Solar Maximum Mission (SMM). Since then,  $P_{\text{Rg}}$  got detected in the interplanetary magnetic field in the Earth's vicinity (Cane et al., 1998) and virtually all heliophysics data sets such as various types of flares, photospheric magnetic flux, and group sunspot numbers. Those studies also reported  $P_{\text{Rg}}$ -related mid-term periodicities of ~128, ~102, ~78, and ~51 days, called the Rieger Type Periodicities (Dimitropoulou et al., 2008) that arise as modulations of  $P_{\text{Rg}}$ :  $5/6 P_{\text{Rg}}$ ,  $2/3 P_{\text{Rg}}$ ,  $1/2 P_{\text{Rg}}$ , and  $1/3 P_{\text{Rg}}$ , respectively. Various mid-term periodicities and their modulations were reported as well in almost all heliophysics data types. Those include sunspot numbers, solar flare index, solar radio flux, proton speed, and others, except for the coronal index and 10.7 cm solar flux (Forgács-Dajka and Borkovits, 2007). Most of those studies indicate a leading (longest) periodicity ranging from 152- to 158-days, which appears to be dominant especially in the time phase from ~1979–1983 corresponding to the solar activity maximum (Chowdhury et al., 2008).

Various proposals exist as to the origin of the underlying resonant process behind the  $P_{\text{Rg}}$  and its modulations and harmonics, including possible influences of planetary constellations on the Sun, e.g., Kurochkin (1998) and Abreu et al. (2012). One of the few remaining undisputed such claims is by Bai and Cliver (1990), who suggested that the  $P_{\text{Rg}}$  behavior could be simulated with a damped, periodically forced nonlinear oscillator, which exhibits both periodic and chaotic behavior. The generation of Mars seismicity tidally-resonantly is supported additionally by the facts that mechanical resonance can induce both small earthquakes (Ferrazzini and Aki, 1987) and small marsquakes (Suemoto et al., 2020; van Driel et al., 2021) and that both strong earthquakes (Omerbashich, 2020a) and strong moonquakes (Omerbashich, 2020b) occur at tidal resonance periods. Besides, externally forced variations in the interplanetary magnetic field can give rise to surges of currents in the crust, which in turn can trigger seismicity (Simpson, 1968). An alternative mechanism is the planetary angular velocity changes induced by a magnetohydrodynamic coupling between the solar and planetary magnetic fields (*ibid.*), but Mars lacking a magnetic field forbids this. The recent MAVEN mission confirmed the former scenario by detecting externally forced electromagnetism on Mars (Ramstad et al., 2020).

A more inclusive explanation of  $P_{\text{Rg}}$  and its modulations is also possible so that many of the previously given reasonings are with merit simultaneously, and the Solar system is a host to an interplay of resonant feedback loops among individual planets and the Sun. In either case, the same agents that force solar activity could be responsible for at least some geomagnetic and seismic activity (Odintsov et al., 2006).

A primary underlying process drives both heliophysics and areophysics, causing the tidal-resonant rupturing response that the InSight lander sampled. Since the InSight lander collected data during the last solar minimum, Martian seismicity could intensify in rate and magnitude during future solar maxima. Because Mars responds significantly at minima as well, Figure 2 and cf. reanalysis of Viking 2 data by Lorenz et al. (2017), while the Sun responds at maxima only, Mars is closer to the source of the primary process, which then likely is of Jovian origin. An extensive study by Simpson (1968), showing that the frequency of non-declustered 22561 global M5.5+ earthquakes spanning 13.5 years and their weaker foreshocks and aftershocks also peaked at solar minimum, supports this conclusion. If so, then it could be that the  $P_{\text{Rg}}$  arises due to Jupiter's magnetic field currently undergoing a polarity reversal or a transition between different dynamo states, as implied from the recent Juno mission (Moore et al., 2018). Before the Juno mission, Pap et al. (1990) had offered an intuitive yet analogous explanation suggesting that the temporary existence of a  $154 \pm 13$ -days period is related to an emerging strong magnetic field.

This result, especially the degeneration of  $1/3 \cdot P_{\text{Rg}}$  into a  $3/11 \cdot P_{\text{Rg}}$  split peak with the second-highest significance level despite sub-band clustering, Figure 2, indicative of a varying anisotropy and therefore possibly surging interplanetary magnetic field as felt in the Mars vicinity, warrants landing seismic probes on other planets and moons. Such seismic missions have been proposed recently to Europa and Titan (Lorenz and Panning, 2018) and could be used to map the extent of the Rieger resonance in near real-time.

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