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Estimation of the seismic moment release rate of Mars from InSight seismic data

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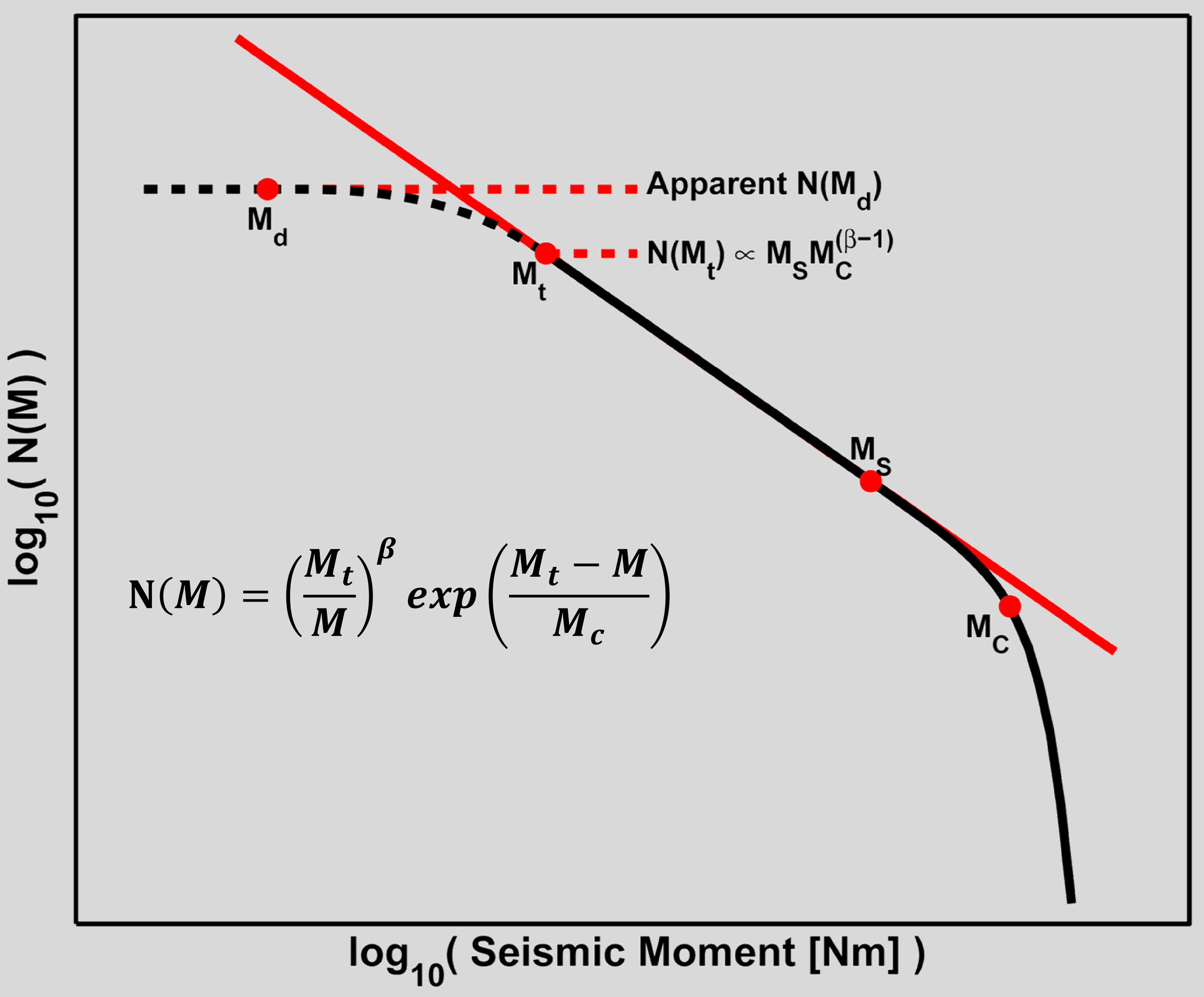
Introduction Seismicity models for Mars usually estimate the long-term average annual seismic moment rate, and also the average annual event rate. This holds for estimations based on geological evidence (Golombek et al., 1992, Golombek, 2002, Taylor et al., 2013) as well as for models based on thermal evolution and cooling of the Martian interior (Phillips, 1991, Knapmeyer et al., 2006, Plesa et al., 2018). All studies are compatible with the conclusion based on the non-observation of any unambiguous event by Viking (Anderson et al., 1977, Goins & Lazarewicz, 1979) that Martian seismicity lies somewhere between that of the Moon and that of the Earth.

We developed tools to derive reasonable estimations of the annual seismic moment rate from a number of events as small as one, provided that the observed events are beyond the global completeness threshold for observable events. Numerical tests as well as evaluation of terrestrial data shows the feasibility of the approach.

Conclusions: It is possible to arrive at reasonably accurate moment rate estimations within a relatively short time (3 months on Earth) and using a small number of events, i.e. one to ten. A paper describing our method, including extensive tests on simulated and real event catalogs, is in print at BSSA.

State of Affairs on Mars: At the time of writing, the planet does not cooperate. The number of currently observed events (0) allows drawing conclusions only by comparison with modeled event rates. The interpretation of non-observations depends strongly on assumptions concerning e.g. Q values. It nevertheless appears that the Knapmeyer et al. (2006) "StrongMany" model does not describe Mars.



We adopt the **Tapered Gutenberg-Richter** distribution (TGR, e.g. Kagan, 2002) to describe the size-frequency distribution of Marsquakes. The TGR tapers down the power law of the **classical Gutenberg-Richter** distribution with an exponential function and gives the number of events exceeding seismic moment M by the expression shown in the figure. The catalog is assumed to be complete for events with $M>M_t$. In this distribution, moment rate and event rate are connected by

$$\dot{M}_S = \dot{N}(M)\frac{\Gamma(2-\beta)}{1-\beta}\frac{M^\beta}{M_c^{\beta-1}}exp\left(\frac{M}{M_c}\right) \quad (1)$$

Considering only the strongest event observed during n years (the **L**argest E**V**ent Eve**R**), we find that, as it approaches M_C (while events significantly beyond M_C are very unlikely)

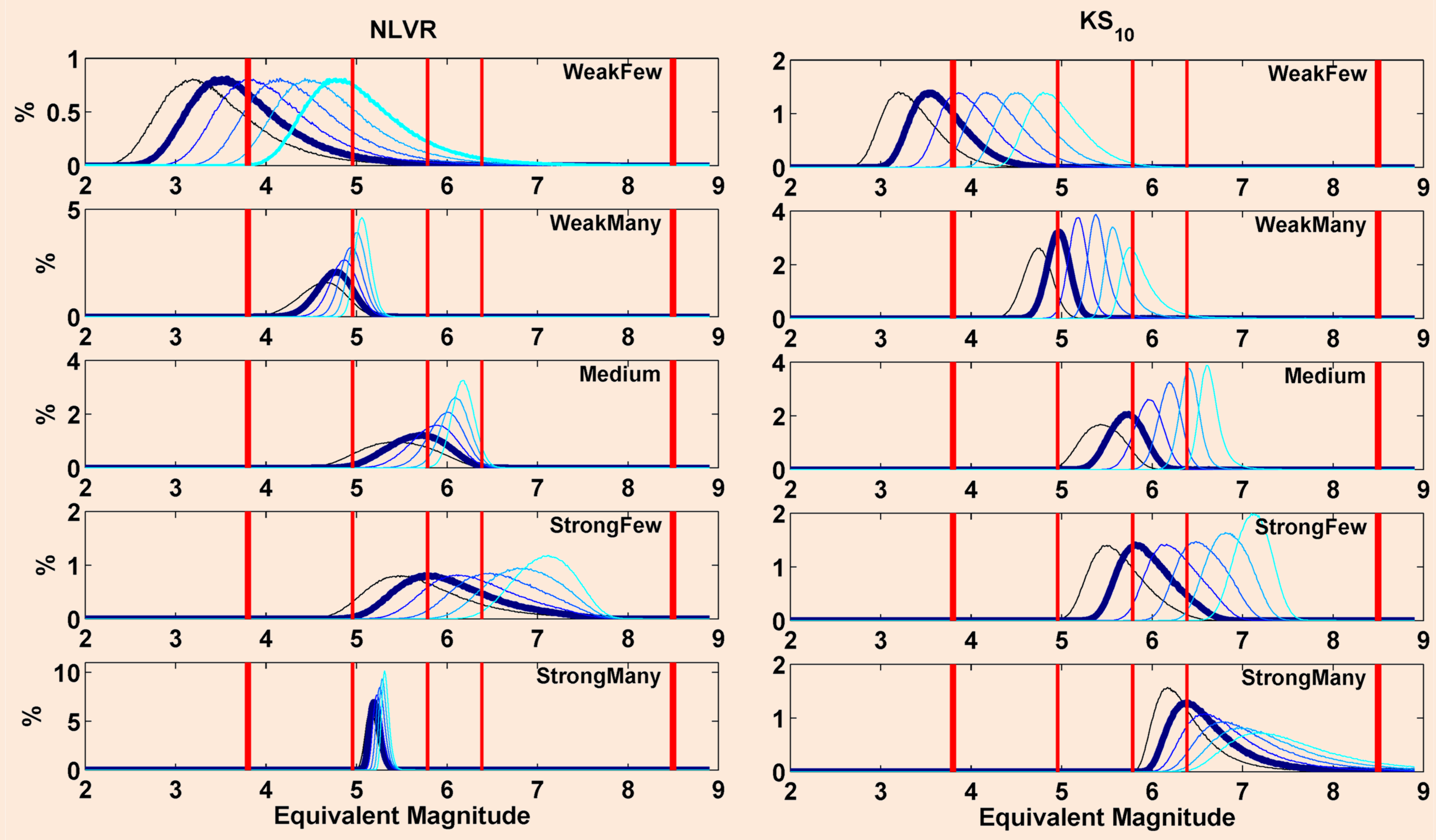
$$\dot{M}_S \approx \frac{1}{n}\frac{\Gamma(2-\beta)}{1-\beta}M_{LVR} \quad (2)$$

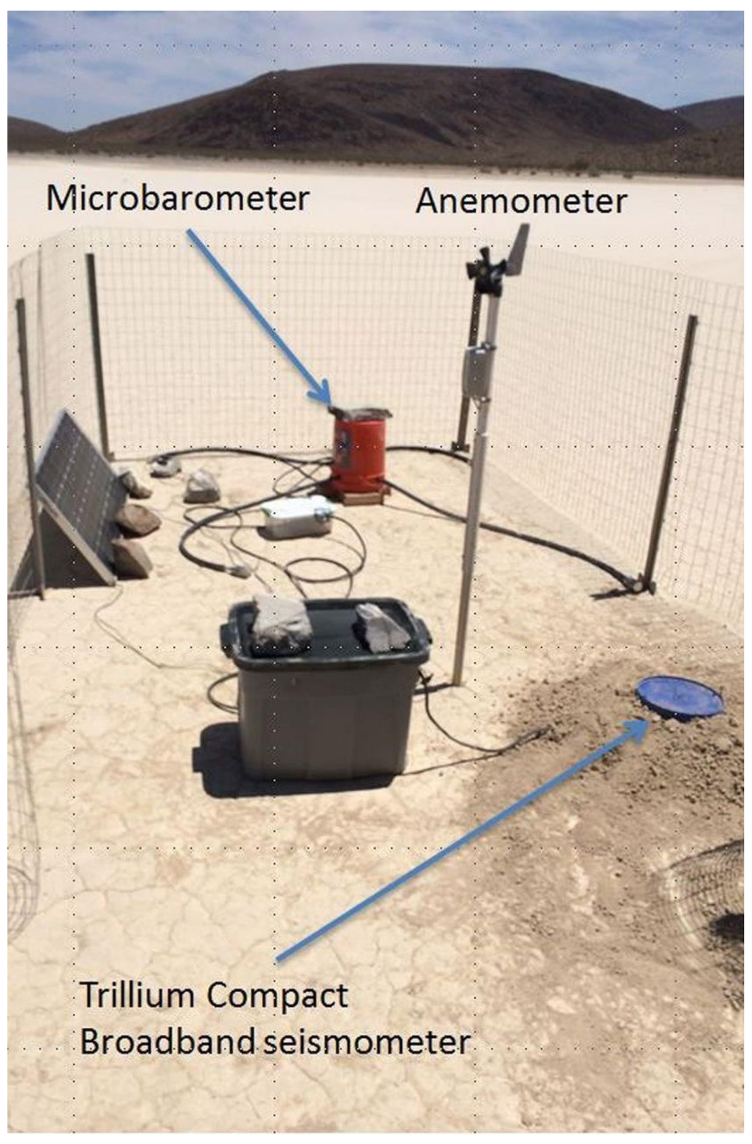
To evaluate the k largest events one has to replace M_c in eq. (1) by the bias estimator of Kagan & Schoenberg (2001)

$$\tilde{M}_c - \tilde{M}_{bias} = \frac{\sum(M_i^2/k) - M_t^2}{2[M_t^2\beta + (1-\beta)\tilde{M}]} - \frac{(\beta-1)[2M_t^3 + 3M_t^2\tilde{M}_c\beta + (\sigma^2+\tilde{M}^2)(6\tilde{M}_c - 3\tilde{M}_c\beta - 2\tilde{M})]}{4k[M_t\beta + (1-\beta)\tilde{M}]^2} \quad (3)$$

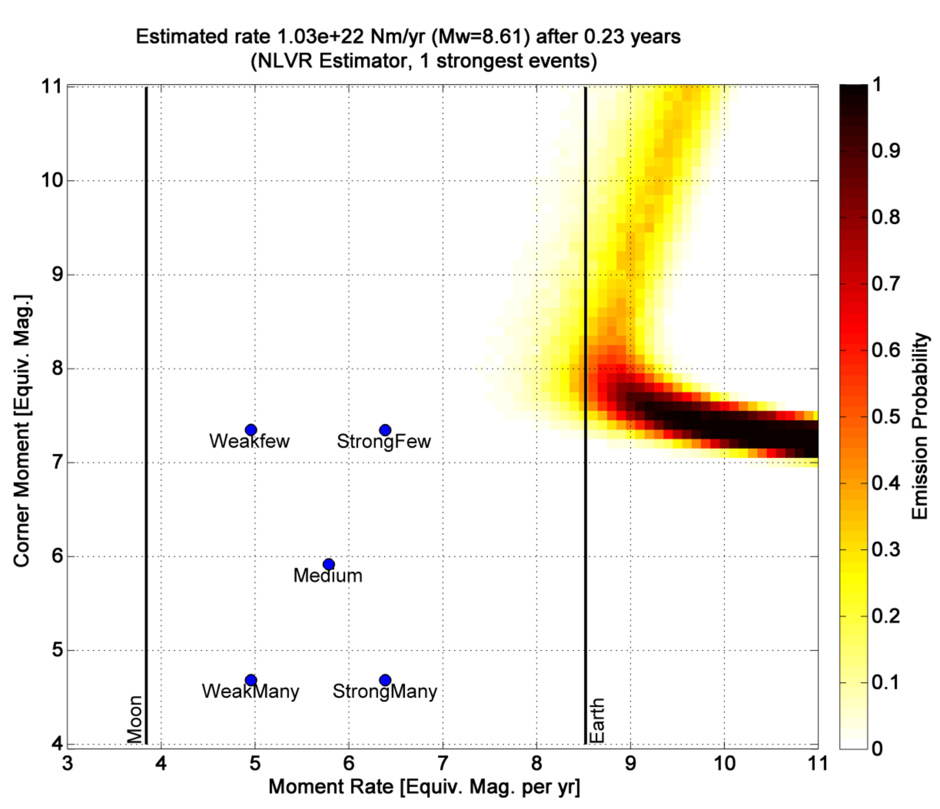
where $\tilde{M}$ is the arithmetic mean of the individual moments. We call (2) the **NLVR estimator** (for **N**ormalized **L**argest E**V**ent Eve**R**) and (1), with (3) inserted, the **KS$_k$ estimator**.

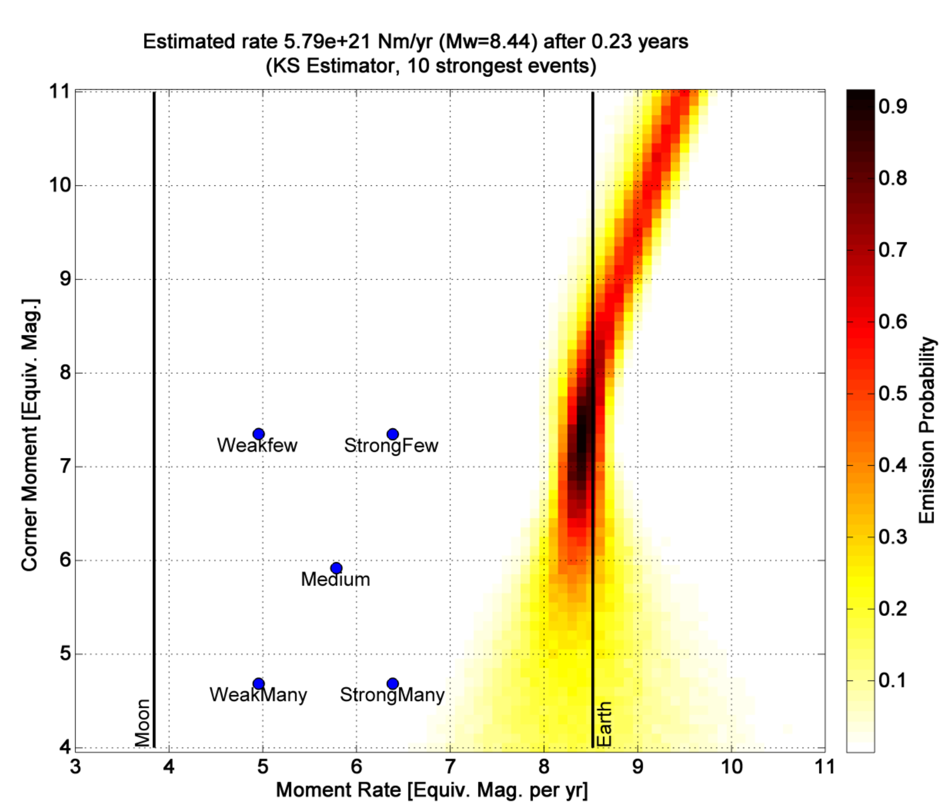
Synthetic Tests: Among other, we tested the two types of estimators extensively with synthetic event catalogs. Here we show catalogs for registration times of 1 (thin black), 2 (bold dark), 4, 8, 16, and 32 (cyan) years for the five end member scenarios of Knapmeyer et al., 2006. For each duration, we evaluate 10^6 catalogs and plot PDFs of obtained rate estimations. Vertical red lines, from left to right, correspond to the seismic moment rate of the Moon HFT events ($7.27 \times 10^{14}\ Nm/yr$), the Mars "weak" ($3.42 \times 10^{16}\ Nm/yr$), "medium" ($5.99 \times 10^{17}\ Nm/yr$), and "strong" ($4.78 \times 10^{18}\ Nm/yr$) scenarios, and the Earth as obtained from the GCMT catalog for 1976 to 2018 ($7.61 \times 10^{21}\ Nm/yr$). All catalogs were generated with a slope of $\beta = 0.625$ (other tests show that using an incorrect slope has little influence).
Bias and variance of the estimation depend on the actual moment rate and the time covered by the catalog. Long durations do not necessarily provide smaller biases. Instead of taking the estimator output at face value it is thus more useful to determine how likely a certain model is to result in a given rate estimation.
By scanning the parameter space of moment rate and corner moment it is then possible to assess which parameter combination is most likely to reproduce the rate obtained from observation.





Experiment A Nanometrics Trillium Compact seismometer was buried in a dry lake bed about 1 km southwest of Deep Space Network Antenna "Mars" in the Goldstone area (Lorenz et al., 2015). The seismometer operated from 05.06.2014 to 29.08.2014 (uptime 68d of 86d) at a sampling frequency of 100 Hz, re-sampled to 2 Hz to resemble the continuous data stream of InSight SEIS.
During this time, the USGS NEIC catalog lists 304 events worldwide with magnitudes of 5 and larger, 134 of these are visible in the Goldstone data. We evaluate NEIC magnitudes of the 10 largest events to estimate the Earth's moment rate.





NLVR Moment Rate Estimation: How likely does a tapered Gutenberg-Richter distribution emit a NLVR (i.e. using 1 event) or KS$_{10}$ (i.e. using 10 events) estimate as obtained from the Goldstone detections? For each combination of moment rate and corner moment, we evaluate 1000 synthetic catalogs and count the fraction of NLVR and KS10 estimates that are within 0.2 magnitude units from the value derived from the Goldstone experiment. Vertical lines: normalized sum of all Moon HFT resp. GCMT events, dots represent the Mars seismicity models of Knapmeyer et al. (2006).

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