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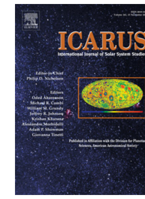

Note

Empirical recurrence rates for ground motion signals on planetary surfaces

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ABSTRACT

We determine the recurrence rates of ground motion events as a function of sensed velocity amplitude at several terrestrial locations, and make a first interplanetary comparison with measurements on the Moon, Mars, Venus and Titan. This empirical approach gives an intuitive order-of-magnitude guide to the observed ground motion (including both tectonic and ocean- and atmosphere-forced signals) of these locations as a guide to instrument expectations on future missions, without invoking interior models and specific sources: for example a Venera-14 observation of possible ground motion indicates a microseismic environment mid-way between noisy and quiet terrestrial locations. Quiet terrestrial regions see a peak velocity amplitude in mm/s roughly equal to $0.3*N^{(-0.7)}$, where N is the number of "events" (half-hour intervals in which a given peak ground motion is exceeded) observed per year. The Apollo data show endogenous seismic signals for a given recurrence rate that are typically about 10,000 times smaller in amplitude than a quiet site on Earth, although local thermally-induced moonquakes are much more common. Viking data masked for low-wind periods appear comparable with a quiet terrestrial site, whereas a Venera observation of microseisms suggests ground motion more similar to a more active terrestrial location. Recurrence rate plots from in-situ measurements provide a context for seismic instrumentation on future planetary missions, e.g. to guide formulation of data compression schemes. While even small geophones can discriminate terrestrial activity rates, observations with guidance accelerometers are typically too insensitive to provide meaningful constraints (i.e. a non-zero number of "events") on actual ground motion observations unless operated for very long periods.

1. Introduction

Much of what is known about the Earth's interior is due to seismological studies and there is accordingly interest in using similar methods on other planetary bodies (e.g. Lognonné and Johnson, 2010). A challenge often confronting mission designers (e.g. Lorenz, 2012) is an expectation of how much observable ground motion there may be, since this determines the sensitivity required and/or the mission duration needed to observe some number of events exceeding some amplitude threshold. Similarly, a basis may be sought to define specifications on the vibration generated by lander systems in missions (e.g. the Europa Lander – see Hand et al., 2017) that seek to avoid the expense of external deployment of instrumentation. A further application of recurrence information is that the choice of data selection and compression schemes (e.g. triggered sampling) may depend on the expected number of events.

One approach is to forward-model the problem (e.g. Knapmeyer et al., 2006; Ceylan et al., 2017; Panning et al., 2015; 2017), positing some annual average moment release through a distribution of event sizes, with events randomly located, and then to apply some estimate of crustal attenuation to derive the ground motion at a given measurement station.

A more parsimonious alternative, yet one that to our knowledge has not been systematically applied in the planetary literature, is to use data from an individual terrestrial seismic station as an analog for a planetary instrument, and to examine existing (albeit very limited) planetary seismic datasets in order to establish general order of magnitude expectations of ground motion (of any type) in a variety of planetary settings. We emphasize that we are not in this paper attempting to estimate the intrinsic seismic/tectonic vigor of the bodies considered – not only would this demand rather better data than exist, but would also necessitate consideration of source depths, attenuation models and so on. Our goal is only to outline a basis of what ground motion might be expected to be ob-

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served if an instrument with given sensitivity were deployed for some specified length of time at a location ' like the Moon', or ' like a tectonically-active site on Earth'. Although perhaps naïve to seismologists, such comparisons are useful in communicating expectations to colleagues from other disciplines, such as spacecraft engineers.

2. Seismic data

2.1. Earth

Our principal basis for comparison is a set of seismic records drawn from three Global Seismic Network stations. We analyzed 2 years of data (arbitrarily chosen to be 2010 and 2011). Data were downloaded from the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC) and processed using the seismological Python program ObsPy (Krischer et al., 2015). For each station, the processing was performed on the vertical BHZ channel, which included broadband data (from a Streckeisen STS-1 V/VBB sensor with a flat ground velocity response from 0.1 s to 360 s for BFO and from a KS-54,000 borehole instrument with a flat ground velocity response from 0.2 s to 333 s for MSVF and MIDW) sampled at 20 Hz.

The three stations chosen are

1. BFO (Black Forest Observatory, Germany). BFO is a quiet station in the middle of a continent far from tectonic boundaries. This defines a quiet terrestrial case, where much of the ground motion spectrum is from distant events.
2. MIDW (Midway Island). This station is also in the middle of a plate (in this case the Pacific oceanic plate), far from tectonic boundaries on a small coral atoll, so is not very active seismically. However, the station has a higher ambient noise level due to the production of microseisms by nearby ocean waves, and Midway is also somewhat exposed to typhoons.
3. MSVF (Monasavu, Fiji). MSVF is also on an oceanic island, although the station is located further from shore than MIDW in a mountainous region in the island's interior. It is also near one of the most tectonically active regions in the world, the Fiji-Tonga subduction zone so it sees a large amount of seismic activity.

The seismic data were read in, and the instrument response was removed to produce ground velocity. The data were filtered between 0.01 and 2 Hz to be representative of a relatively modest instrument bandwidth (the relatively minor effect of narrower and broader responses are discussed in the Supplemental Information), and the peak amplitude in half-hour blocks was recorded (thus 17,520 amplitudes in the two years). These peak amplitudes were converted to recurrence intervals by simply counting the number of blocks with peak amplitudes exceeding a given ground velocity and dividing by the record length. Throughout this paper we consider seismic signals with a nominal frequency of order 1 Hz: the large dynamic range of the parameter space discussed in this paper makes the conclusions robust to differences due to frequencies differing from 1 Hz by less than an order of magnitude, and we neglect the modest differences in bandwidth associated with different sensors (figure S2 shows that the terrestrial results are relatively insensitive to using different bandwidths). Although displacement and acceleration also have virtues as metrics of ground motion, for the sake of using a single quantity, we display ground velocity (the natively-sensed property by geophone-type instruments, including Viking and Venera). A useful guide to the presentation of seismic noise and data in its various forms is that by Bormann 1998; see also Lorenz (2012) and Bormann and Wielandt (2012).

We recognize that slightly different results might be obtained with different frequencies sensed. Similarly we consider only vertical motion (only vertical data are available for Venus and Titan), whereas horizontal sensing may be more sensitive e.g. to wind noise or to different types of seismic wave. However, the present order-of-magnitude reconnaissance of the problem is not strongly sensitive to these factors.

The block size (i.e. what defines an "event" in our portrayal) is important but our choice here can be just justified post-hoc by the success of a half-hour block in discriminating three different sites with different characters. *A priori* the block should be longer than a typical source event but not so long as to frequently encounter multiple events in a single block and thus count them as only one. The wavetrain (coda) from a single earthquake is typically some tens of seconds on Earth but sometimes much longer. However, if we were to choose a block size of only a minute, a single tropical storm that causes enhanced microseismic activity for a day or two would indicate a thousand "events", a perhaps disproportionate emphasis. Thus it must be recognized that the shape and location of the curves in Fig. 1 is dependent on the choice of block size. A half-hour block (i.e. 48 blocks per day) is short enough to make a reasonable comparison with the thermal moonquakes (see later) of which there were typically several per day, lasting a minute or two.

The results for 30 minute blocks are plotted in Fig. 1. The nearly continuous background noise amplitude is apparent in the recurrence intervals equal to about 100 events per year or more, and this clearly show how ocean noise dominates MIDW, while MSVF is generally quieter (i.e. quieter for more frequent events), and BFO quieter still. The proximity of tectonic activity is obvious in the strong but less frequent ground motion events, with MSVF reaching annual amplitudes of over 10 cm/s. The Supplementary Information (especially figure S1) shows that for the BFO site, most of the events with amplitudes below 1 μm/s are due to small, and thus by implication, local quakes.

Also shown in Fig. 1 are results derived from the US Geological Survey Seismic Hazard Map (Frankel et al., 2005) for very large but low probability ground motions. This product indicates the 1 Hz seismic acceleration in units of g, or the acceleration due to gravity at the Earth's surface, for which a 10% probability of exceedance in 50 years is expected, for civil engineering applications (e.g. safety of dams, nuclear power plants etc.). In the middle of the continent (Texas to N. Dakota) this value is only about 0.015 g, whereas the maximum, near the San Andreas fault in Southern California, is about 0.8 g. We can interpret the acceleration as a velocity at 1 Hz by dividing by 2π to yield $\sim$20 and 1200 mm/s respectively: a 10% chance of exceedance in 50 years translates into an expectation of one event in 500 years, or 0.002/yr. It is seen that the mid-continent point falls as a quite reasonable extrapolation of the BFO seismic recurrence intervals in our analysis above, and the California value is more consistent with the more active sites MIDW and MSVF, although the extrapolation of MSVF would likely plot significantly higher.

All the terrestrial data appear above a 1 μm/s threshold well within the capabilities of a simple geophone near its resonant frequency (e.g. Rodgers, 1994 calculates a theoretical half-octave root-mean-square noise level of 1E-8 ms^{-2} at 2 Hz for a small (70 g) L-22D geophone, corresponding to a ground motion noise of $\sim$0.001 μm/s). If an instrument with a 1 μm/s threshold were deployed and operated for 1 day, it would detect $\sim$10 periods with a ground motion exceeding instrument self-noise even at a quiet site such as BFO, or some dozens of events at MSVF, and hundreds at MIDW, discriminating the different seismic environment at these sites. Note that this approach does not make any assumptions about the source of the ground motion, which may be tectonic events or ambient noise excited by the oceans.

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