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Impactor mass estimation for three large impacts detected by the Apollo seismometers

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Abstract

Meteoroid impacts are important seismic sources on the Moon. We have estimated the impulse response and frequency properties of some largest meteoroid impacts and determined the possibility to use, in the future, such impacts to study the thickness and structure of the lunar crust. We show that their masses can be estimated with rather simple modeling technique and that high frequency seismic signals have reduced amplitudes due to a relatively low (about 1sec) corner frequency resulting from the duration of the impact process and the crater formation. If synthetic seismograms computed for a spherical model of the Moon are unable to match the waveforms of the observations, they nevertheless provide an approximate measure of the energy of seismic waves in the coda. The latter can then be used for an estimation of the mass of the impactors, when the velocity of the impactor is known.

1. Source function

Let us consider the source excitation process for an impact where an impactor is instantaneously absorbed by the surface without ejecta generation. The seismic force can be modeled as a point force

$$\mathbf{F_0}(t,\mathbf{x})=m\mathbf{v}\ \delta\ (t)\ \delta\ (\mathbf{x}-\mathbf{x}_s) \qquad (1)$$

where m is the mass, $\mathbf{v}$ is the velocity vector (v being the velocity amplitude. Following [1], we assume a simple model for the seismic source function, namely, a time-dependent force acting downward on the surface of the planet during the impact, which takes into account the fact that part of the seismic force could be associated with ejecta material [2]. Let the seismicforce function be in the form

$$f(t,\mathbf{x})=m\mathbf{v}\delta(\mathbf{x}-\mathbf{x}_s)g(t)=\mathbf{F_0}(t,\mathbf{x})*g(t), \qquad (2)$$

$g(t)=1+\cos\omega_1 t$ for $-\pi/\omega_1<t<\pi/\omega_1$, $g(t)=0$ otherwise.

We define the seismic amplification parameter as S=I/mv, I is the seismic impulse, defined as an intergral of the equivalent force $f(t)$, $\tau=2\pi/\omega_1$ to denote the time-duration of the excitation process. The Fourier transform of g(t) is proportional to ω^{-3} for angular frequencies higher than the cutoff angular frequency ω_1. That is why we expect the seismic acceleration spectrum, which varies as ω^3 at low frequency for an impact, to be flat after the cutoff frequency and even to decrease due to additional effects such as attenuation.

The amplitude of the spectrum recorded at a given epicentral distance D can be approximated as

$$\hat{s}(\omega)=B\omega^3\exp(-\frac{\omega t_{prop}}{2Q})\times\hat{g}(\omega) \qquad (3)$$

where B is a constant depending on the source impulse and epicentral distance.

First we tested this source model on artificial impacts spectrum. We have determined, the best values for Q, τ and B in (3). For SIVB's and LM impacts we have τ=0.6 sec and 0.45 sec, respectively

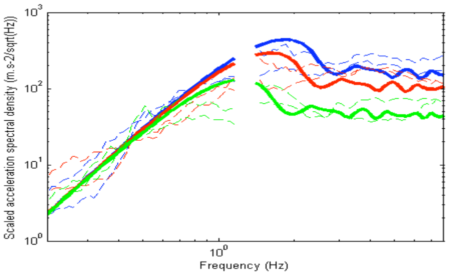

Figure 1:Acceleration spectral density for three large meteoroids impacts. The blue, red and green lines are the theoretical scaled acceleration spectral densities calculated for simulated events (13 January, 25 January and 14 November 1976) with the assumed surce function in form of (2).

and a very good fit explaining practically for all the data and a very high quality factor. In contrast, for the seismic force in the form of (1) we find not only an unrealistically low Q values, but, moreover, a much lower variance reduction. The same fit was done for large meteoroids impacts. Fig. 1 shows the results for the best values (τ = 0.7, 0.8 and 1.05 sec for the impacts on day the 13th and the 25th of January and the 14th of November, respectively).

2. Impactor impulse estimation

The validity of this approach was confirmed for the artificial impacts (Fig. 2). We have selected for our analysis three large meteoroids impacts (Table) and determined the values of the seismic impulse by matching the energy in the observed and modeled waveforms (Fig. 3).

We generally observe amplitudes within 10-30 % of those estimated by synthetic seismograms. The dispersion is in agreement with estimates [2], but here the agreement is found directly with the synthetics. We used the HTML software available at http://keith.aa.washington.edu/craterdata/scaling/index.htm to estimate the momentum associated with ejecta for a lunar regolith target and the amplification factor S. The mass and size of the meteoroids are (15-32)x10^3 kg and 2.1-2.7m in diameter, for the density of 3000 kg/m^3 and a 20 km/s impact velocity.

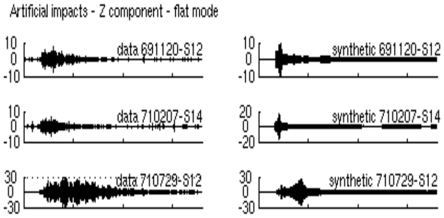

Figure 2 Synthetic lunar seismograms (right) and data set recorded at the stations (left) for some man-made signals. The abscissa is the duration (sec), the ordinate is the amplitude (in DUs). The date of the event and the name of the station recorded the event are given.

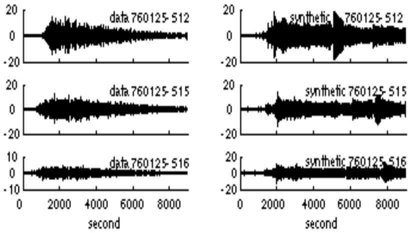

Figure 3 Synthetic lunar seismograms with momentum listed in Table compared with data set recorded at the stations (left) for the event 25 January 1976 See also caption to Figure 2.

3. Conclusion

Current estimates of the size of the meteoroids (diameter of 2-3 meters) indicate that they could create craters of about 50-70 meters in diameter: it might therefore be possible for the NASA Lunar Reconnaissance Orbiter mission to detect these craters. These impacts were insufficient to generate surface waves above the detection threshold of the Apollo seismometer. Future seismometers must have performances at least 10 times better than Apollo in order to get these surface waves from comparable impacts. Such a resolution will also allow the detection of several impacts of low mass (1-10 kg) at a few 10s to hundred km of each station, which might be used to perform local studies of the crust.

Acknowledgements

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