Characterization of Scattering in Lunar Seismic Coda. Jean-Francois Blanchette-Guertin[1], Catherine L. Johnson[1,2], Jesse F. Lawrence[3]. [1]University of British Columbia (6339 Stores Road, Vancouver, BC V6T 1Z4, CANADA; jguertin@eos.ubc.ca), [2]Planetary Science Institute (1700 Fort Lowell, Suite 106, Tucson, AZ 85719), [3]Stanford University (397 Panama Mall, Mitchell Building, Room 360, Stanford, CA 94306).

Introduction: Data collected during the Apollo Passive Seismic Experiment (APSE, 1969-1977) have been pivotal in understanding lunar interior structure. However, with a few exceptions [1,2,3] analyses of seismic phases other than initial P and S arrivals has proved challenging due to the following characteristics of lunar seismograms: long durations (the seismic coda), small initial amplitudes, small maximum amplitudes, and a slow build up of energy from the onset of the waveform to the maximum amplitude. The long coda (typically ~60 minutes) result from low intrinsic attenuation and high scattering [4], and represent a largely untapped source of information about the lunar interior, in particular about its scattering properties.

Here we analyze the coda from 446 higher quality seismograms from different types of lunar events. We characterize the coda via their rise times (time from initial P or S wave arrival to maximum P or S wave amplitude), and their characteristic decay times. We investigate any dependence of these parameters on source type and/or depth, and on source-receiver distance.

We calculate synthetic seismic records for different models of the Moon's interior using a new, modified version of the phonon method [5]. We compare quantitatively those records with the actual lunar seismic data and identify suites of interior structure models that are compatible with the data.

Analyses of APSE Seismograms: Records of deep moonquake (DMQ), shallow moonquake (SMQ), artificial impact (AI) and natural impact (NI) events were visually inspected and seismograms showing clear S-coda were selected for analysis. The quality of the 446 selected signals is similar to those of the DMQ Grade A class described in [6]. The DMQ signals retained originate from 12 different source regions. For all source types, the long period X and Y horizontal channels were combined into a single horizontal component through vector summation (we assume horizontal isotropy).

Each of the seismograms retained was processed as follows: (1) The data is band-pass filtered and de-spiked as described in [6]. (2) If possible, P- and S-wave arrival times were identified. (3) The envelope function was generated using a Hilbert transform and smoothed using a 5 minute running window, keeping the 75th percentile value (empirically determined to retain the characteristic signal amplitude, while reducing the contribution from noise spikes). (4) The maximum amplitude of the smoothed envelope was recorded (A_{max}). (5) An exponential decay curve, $A_0 \exp(-t/\tau_d)$, was fit to the decay of the smoothed envelope with time (t), where τ_d is the characteristic decay time from the time of peak amplitude. A_0 is the initial amplitude of the fit and is typically equal to A_{max}. It is different if the fit does not start at the time of A_{max} due to spikes in the signal that would have affected the results of the fit. A_{max} is preferred over A_0 for further analyses. (6) The S-rise time (τ_{rs}), defined as the time between the S-wave arrival and the time at which the S-coda amplitude reaches its maximum (A_{max}), is calculated.

Results: Dependences of the characteristic decay time and the S-rise time on event magnitude, epicentral distance, and depth were investigated for all types of events. Initial results indicate:

- No dependence of τ_d and τ_{rs}, for any type of event, on depth of occurrence or on event magnitude.
- For DMQ and AI, there is no identifiable dependence of τ_d and τ_{rs} on epicentral distance.
- The short-period vertical channel (SPZ) recordings of SMQ show a dependence of τ_d on epicentral distance, with a correlation coefficient, R = 0.67 (Figure 1).
- For individual events, τ_d on the long-period channels (LP) is always larger than τ_d on SPZ. The LP/SP decay time ratio is about 3 for the DMQs, and 5 for the SMQs.
- On the SPZ component, the average τ_d for SMQ is ~24% shorter than the average τ_d for DMQ. There is no measurable difference in τ_d for SMQ and DMQ on the LP horizontal component.
- The average τ_d on station 14 is shorter than the average τ_d on station 12 for a given event type. These stations are located within 200 km of each other, and lie in similar geological regions. The results may indicate that seismic scattering is dominated by local subsurface structure.

On the SPZ component, The SMQ dependence of τ_d on epicentral distance may result from interactions between two sets of waves: 1) direct waves from the lower hemisphere of the quake, and 2) scattered surface reflections from the upper hemisphere of the quake. The near-quake scattered surface reflections should arrive later within the near-receiver scattered coda of the direct waves, extending the duration of

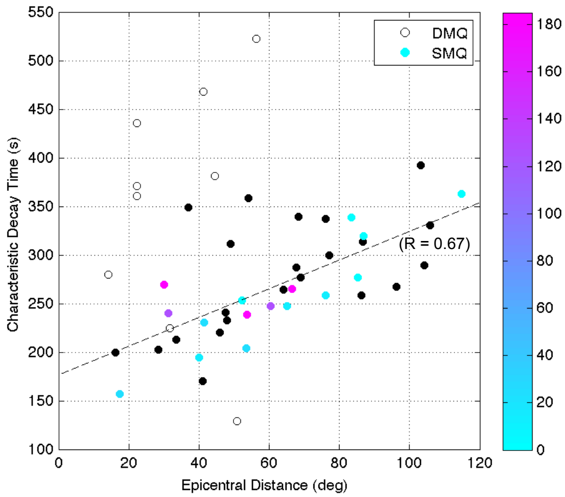

Figure 1: Characteristic decay time (τ_d) from SPZ versus epicentral distance (Δ) for DMQ and SMQ. The dashed line is a weighted least-squares straight line fit to the SMQ data (weights are based on quality of exponential decay fits). Color represents the depth of SMQs, in km [7], black means depth was assumed to be 100 km [8]. Events from all four stations are shown.

coda. The longer DMQ coda may result from several possibilities: a) multiple reflections from deep moon interfaces (e.g., a core-mantle boundary), b) a deep moon scattering region, or c) different quake mechanics (i.e., longer source time function). The differences between SP and LP results may help identify the scale lengths of heterogeneity responsible for the scattering, and hence possible filters to apply in future investigations.

Synthetic Seismograms: We calculate synthetic seismograms using the phonon method [9, 5], which tracks individual quantized lattice vibrations through a scattering 3D heterogeneous medium such as the lunar subsurface. We assume an isotropic medium with heterogeneous length scales ~1km at unknown orientations within the upper 10km, possibly resembling small-scale heterogeneity within the lunar mega-regolith layer. 10^{10} phonons are emitted from various DMQ and SMQ depths. The phonon amplitudes and times are recorded at the surface. We limit the synthetics to the LP bandwidth and amplitude as well as stochastically model signal degradation caused by limited analog-to-digital resolution with electrical noise (~1-3 digital units) to simulate the quality of the APSE data.

Synthetic seismograms generated where 60% of all phonons scatter within each $1km^3$ region of the "mega-regolith" layer yield long seismic coda with τ_d of ~1400s for events at a depth of 1100km. This is comparable to the observed τ_d (~1500s for DMQ, on long-period horizontal channels). Adding an additional 1km thick surface layer with 0.1km scale length 3D heterogeneity does not significantly alter the LPZ synthetics for the deep events. However, synthetic seismograms for shallow events (20km) do not compare well with the APSE data (τ_d of ~3200s for the synthetic data versus ~1400s for SMQs). Further investigations with SP-filtered synthetics may illuminate the cause for observed differences between the SP and LP component characteristic decay times for the APSE data, as well as the differences between the SMQ and DMQ.

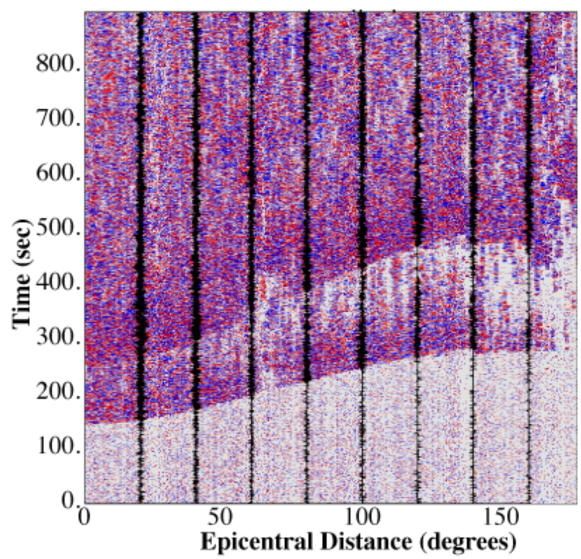

Figure 2: Synthetic seismograms for a DMQ (1100km) using a 10km thick mega-regolith scattering layer yield long decay times at long periods. Positive and negative amplitudes are illustrated as red and blue. Black seismograms are illustrated at 20° intervals.

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