Laboratory Simulations of Martian Meteorite impacts and Their Seismic Signatures

How hard do we need to hit Mars to see what it’s made of?

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Key issues for using impacts as seismic sources for Mars

• Impacts are complex, poorly constrained sources of seismic energy: How well is the impactor momentum transferred to seismic waves?

• There are large uncertainties in the seismic response of the Martian regolith and interior.

• Given the current expectations of naturally occurring impacts what can we learn about the Martian interior?

• Beyond calibration, would a targeted impact provide additional information for scientific discovery?

Lunar impacts recorded by the Apollo 12 Lunar seismic network [Latham et al, 1970].

Simulation of a 500Kg projectile, 5km/s, recorded 50 degrees away.
Objectives of the Mars Analog Experiment

• Characterize the transfer of momentum from an impacting object to seismic waves.

• Determine the planet’s surface-impulse seismic response for a range of Martian interior models that include realistic layering, attenuation, and heterogeneity assumptions.

• Combine (1) and (2) with a modern model of the Martian impactor space-time-size distribution to estimate the amplitude and frequency of impact-induced seismicity over the planet’s surface during one Martian year, and evaluate its potential for exploration of the planet’s interior.
AVGR Facility

Simplified Gun Range Diagram
Seismic Setup

Endevco 2256A-10
Accelerometer
±500g Dynamic range

Recorded at 10^5 Hz
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<th>Target Material</th>
<th>Projectile Weight (gr)</th>
<th>Projectile Velocity (km/s)</th>
<th>Angle from horizon (°)</th>
<th>Measured Pressure (Torr)</th>
<th>Pressure (Atm)</th>
<th>Pressure (psi)</th>
<th>% of Mars atmosphere</th>
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Shot #13 – Sand – 1Km/s - Vertical
Post shot measurements
Shot #07 data
Obtaining a Source Time Function

• Measure Material properties ($V_p$, $V_s$, $Q_p$, $Q_s$)
• Calculate a Green’s function $g(t)$ for the laboratory setting
• Deconvolve Green’s function from Data $d(t)$ to obtain source time function $f(t)$

$$d(t) = f(t) * g(t) \Leftrightarrow D(\omega) = F(\omega)G(\omega)$$

• Compare impact to known projectile momentum

$$P = \int_{t_0}^{\infty} f(t) dt \approx mv$$

• Estimate seismic energy and compare to projectile kinetic energy
Shot #07; Channels 1-3

\[ v_p \approx 250 \text{m/s} \]
Estimating $Q$

\[
\frac{1}{Q(\omega)} \equiv - \frac{\Delta E}{2\pi E}
\]

\[
A(x) = A_0 \exp\left[ -\frac{\omega x}{2cQ} \right]
\]

\[
Q(\omega) = -\frac{\omega x}{2c \ln\left[ A(x) / A_0 \right]}
\]

$Q \approx 6 (!)$

Signal Power

Frequency (Hz)
Green’s function for a vertical impulse

Low $Q$ impacts the signal amplitude and effectively applies a low-pass filter to the signal.
Obtaining the STF through deconvolution

\[ f(t) \Leftrightarrow F(\omega) = \frac{D(\omega)}{G(\omega)} \]

Deconvolve \( g(t) \)

From \( d(t) \)

To obtain \( f(t) \)
Estimated Impacts vs Measured Projectile Momentum

Vertical Sand Shots

- Projectile Momentum (Kg*m/s)
- Impact (Kg*m/s)

<table>
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<th>Momentum (Kg*m/s)</th>
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Calculating Seismic Energy

\[ u(t) = \frac{f(t)}{4\pi\mu r} \]

- \( u(t) \) – Displacement
- \( \mu \) – Rigidity
- \( r \) – Radial distance

We choose an integrable source time function \( f(t) \) (aka Jeffreys Pulse) defined as:

\[ f(t) = cte^{-\alpha t} \]

\[ P = \int_{0}^{\infty} f(t) \, dt = mv \]

\[ c = \alpha^2 P \]

- \( \alpha \) – Time decay constant derived from estimate of \( f(t) \)

It can be shown that the Seismic Energy \( E_s \) is approximately

\[ E_s \approx 4\pi r^2 \rho v_p \int_{0}^{\infty} u(t)^2 \, dt = \frac{\rho v_p \alpha^3 P^2}{16\pi\mu^2} \]
Calculation of traditional Seismic Efficiency from estimated impact

The Seismic Efficiency is close to the upper limits of past estimates.
Open Issues

1. How do the laboratory experiments scale up to meteorite size impact? (Does the fact that we get nearly perfect momentum transfer at small scales apply at large scale?)

2. What is the effect of a soft low $Q$, thin (10s of meters) layer of regolith on signal strength from:
   - Meteorites / Projectiles ?
   - Marsquakes ?

3. Given (1) What we have learned (and will continue to learn) about the impact process; (2) The range of estimated elastic properties of Mars; and (3) The knowledge of Martian meteorites size and frequency distribution – Could we bound the contribution of meteorite seismic sources towards achieving InSight’s mission objectives?

4. Could a targeted impactor(s) be used to calibrate seismic measurements on the Martian surface (and help towards achieving the mission objectives)?
Water is believed to reside in the Martian Crust in two thermally distinct reservoirs: Shallow Cryosphere, and deeper groundwater.

From Clifford et al [2010]

Groundwater is too deep to be detected by remote sensing.
Prospecting for water with artificial impacts and a single seismometer (InSight)

InSight 2017

Crust without Water Layer

Crust with Water Layer

1km

5km

1km

5km
Backup Slides
Scaling up the laboratory measurement

1. Simulate laboratory impacts using ICL’s I-SALE Hydrocode
2. Match numerical simulation with:
   • Dynamic impact measurements (i.e. movies)
   • Crater measurements
   • Seismic measurements
3. Obtain understanding of the impact process under Martian conditions
4. Simulate real size meteorites
5. Obtain a source time function for meteor-scale impacts on Mars

http://amcg.ese.ic.ac.uk/index.php?title=Crater_formation_in_high_strength_targets
Feed STF into a spectrum of Mars seismic models.
The effect of a soft attenuating layer
What is the size and frequency distribution of Martian meteorites?

HiRISE image of an impact crater 5.5 meters in diameter that formed between January 2006 and May 2008. PSP_010862_1880.

Daubar et al., [2010]