Seismology 3: Extra-terrestrial
Seismology on telluric planets

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New frontiers of Planetary seismology

The interior of the terrestrial planets…
The first success story

von Rebeur-Pacshwitz (Nature, 1889)

A. Mohorovičić (1910)

Oldham (1897)

Lehman (1936)

Oldham (1906)
The first success story

>20000 stations, many of them with direct access to data
• Forget Earth dense Network…
  • Goals of planetary seismology are those of the early 1890-1920 on Earth…

• Past Seismology with 4-5 seismometers….. The Moon

• Near future Seismology with one seismometer…… Mars

• Further future Seismology without seismometer … Venus or maybe Moon
Not in this talks...

- **Jupiter**
  - growing evidence that normal modes are excited continuously to a level close or above from the detection threshold (Gaulme et al., 2011)

- **The Jovian satellites**
  - Europa, Io might be interesting place to go in some decade of this century (see Panning et al., 2006)

- **The small bodies**
  - where seismic waves generate seismic shaking and change the surface morphology (Richardson et al., 2004)

- **The Sun**
  - where normal modes are monitored with a detail we do not have on Earth (e.g. Gizon et al., 2010)

Peter et al., 2011
Lunar seismology... started in 1962...

- Seismometer and Ranger at JPL
- Ranger 3
  1/26/1962
- Ranger 4
  4/23/1962
- Ranger 5
  10/18/1962

Apollo 14 crew training the ALSEP (and seismometer) deployment

Sterile seismometer assembly at Aeronutronic
Apollo seismic network
Lunar quakes zoology

1 Digital Unit (DU) = 0.5 $10^{-10}$ m at 2 sec

Lognonné & Johnson, 2007
Lunar quakes zoology

Moon activity at Apollo 14 station

Lognonné & Johnson, 2007
Deep Moonquakes

- Over 10,000 quakes detected in 7 years
- Small to very small amplitudes
- Triggered by the Earth’s tide
• In the late 1990s, JAXA decided to transfer the “old” tape recorded Apollo data on exabytes in the frame of the Lunar-A penetrator mission.
• Lunar-A was cancelled in 2007, but this effort lead to a renewal of the Apollo seismic data analysis.
• Data are now available in various electronic forms and recovery effort continues...
The most recent Apollo seismic data....
Apollo seismic network

Kawamura et al., 2014
Impact collection and arrival time measurement “noise” or “error”
Typical Inversion in the Apollo case

Seismic data, i.e. arrival times at the stations (3 most of the time)
\( N_{\text{events}} \times 6 \)

Model parameters, i.e. P and S seismic velocities with depth
\( N_{\text{parameters}} \)

Source parameters, i.e. position and times of the quakes
\( N_{\text{quake}} \times 4 \)
\( N_{\text{impact}} \times 3 \)
\( N_{\text{event}} = N_{\text{quake}} + N_{\text{quake}} \)

Practically, in total 319 P & S arrival time data were used to constrain 59 seismic sources, including 185 source parameters and 134 degree of freedom available for internal structure. Large errors for arrival times…

2 approaches:
- get noisy inversions with high resolution
- get less noisy inversion with low resolution by reducing the number of parameters (or layers) and/or by injecting a priori mineralogy
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- get noisy inversions with high resolution
- get less noisy inversion with low resolution by reducing the number of parameters (or layers) and/or by injecting a priori mineralogy
The Lunar Seismic models (with error bars…)

Inversion with many layers

Inversion with a few layers

Figure 5  P- and S-wave velocity models vs depth: green, Goins et al. (1981b), red, Ganepain-Beyneix et al. (2006), blue, Nakamura (1983). The light gray zone is the 80% probability zone of Khan and Mosegaard (2002); The dark gray is the petrology/geochemistry model of Kuskov et al. (2002). Values for mantle velocities and associated 1σ uncertainties for each model can be found in table 1 of Lognonné (2005) and are plotted as colored dashed lines with the same colors for the three first models.
The Lunar Seismic models (with error bars...)

Inversion with a few layers

Direct inversion of mineralogy models
Crustal thickness was estimated to 60 km between 1970-1980 by Toksoz et al. and Nakamura et al.

- This implied a large volume of primary crust and an bulk U content much larger than Earth.

All re-estimations were however providing thinner crust, from 30 km (Lognonné et al., 2003, Beyneix et al., 2007) to 38 km (Khan et al., 2002).
• This apparent contradiction is mainly related to two different models family having *similar travel times*…

Moon receiver function (Apollo 12 site)

Vinnik et al., 2001
Lunar impacts... Lightening the crust

Lognonné and Kawamura, 2014
Lunar impacts... Lightening the crust

Lognonné and Kawamura, 2014
\[\text{mean} = 34 \pm 5 \text{ km}\]

Gravity

Seismology

Chenet et al., 20016
GRAIL Confirmation

Possible fracturation extension below the crust
Impact source properties….

- Natural impacts have a long lasting seismic source likely due to the low seismic velocities of the surface and high (20km/s) impact velocities

Gudkova et al, 2014
Source model (in frequency)

- Low frequency displacement $\Rightarrow$ moment or impulse
- Frequency integral of displacement $\Rightarrow$ energy
Seismic source must take into account both the ejecta and the formation time of the crater

- Ejecta mass are much larger than impactor mass
- Momentum of the ejecta is significant and increase the force
- Formation time leads to cutoff in the 1Hz-10hz range

\[
\vec{f}_0(t) = (m\vec{v} - \vec{p}_{eject})\delta(t)
\]

\[
\vec{f}(t) = \vec{f}_0(t) * g(t)
\]
Ejecta and Seismic source

- Provide an amplification of the point force amplitude ($\sim m v$)
- Low effects for the Apollo artificial impacts
- Significant effect for high velocity impacts, leading to vertical source
- Linearity to the source impulse is found below .5Hz

Lognonné et al., 2009
• Until 2010, Seismology was in a pre-Oldham configuration regarding the lunar core structure.

Lognonné and Johnson, 2007

Core signal from magnetic sounding, Hood et al, 1999

Core signal from libration monitoring, William et al, 2001

Lognonné and Johnson, 2007
• Deep Moonquakes repeat at the same fault at rate of several per months
• Are triggered by the Earth tide

Kawamura et al, 2013

• Are beneath the Apollo stations and lighten the deep Moon interior

Garcia et al, 2013
Seismic discovery of the core (1/2)

Garcia et al., 2011
Weber et al, 2011
Seismic discovery of the core (2/2)

fluid outer core
380 km (Garcia et al, 2011)

Weber et al, 2011
Khan et al, 2006  
( direct inversion of seismic data)

Khan et al, 2007  
( direct inversion of magnetic data)

Gagnepain-Beyneix et al, EPSL, 2006
1620°C (Fe, Anderson and Isaak, 2000)

1490°C (29° Ilmenite, 71% clinopyroxene, Wyatt, 1977)

950°C (Fe-S Eutectic, Fei et al, 1997)

Lord et al, 2010
Our view of the Moon

- Hot mantle with possible partial melting
- Liquid Iron core with light elements, sulfur? 350km?
- Iron inner core?
- Thin Primary crust
- Shallow quakes
- Deep quakes
Moon Future directions...

• SELENE2 (JAXA)
• NF Lunar Network (NASA)

Impacts: Can now be observed also from Earth and will therefore provide free active seismic experiments with 100th

Core: Better sensitivity will allow the detection of core phases on single seismograms

TUTORIAL EXERCISE 1:
WHAT ARE THE AMPLITUDE OF 15 sec SEISMIC WAVES GENERATED BY A SHALLOW MOONQUAKE ON THE MOON?

NRC Decadal report “vision and Voyage for Planetary Science in the 2013-2022 decade”
Over the 35 years since Viking and Apollo, despite many proposals and several mission starts, there have been no further seismic investigations of the interior of any planet... until now!
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A priori seismic models

Dashed line Sohl and Spohn [1997]
Gudkova & Zharkov (2004]
Solid line 50%H, 14% S
Dotted line 70% H, 14% S
Dashdotted line 35% S

Mocquet et al., 1998

Earth like Q dependance
Lognonné and Mosser., 1993

Nimmo, 2012
• Launch: March 4, 2016
• Fast, type-1 trajectory, 6.5 month cruise to Mars
• Landing: September 28, 2016
• 67-sol deployment phase
• One Mars year (two years) science operations on the surface; repetitive operations
• Nominal end-of-mission: October 6, 2018
Payload Elements Deployment challenge: Apollo
Payload Elements Deployment challenge: InSight
**The InSight Payload**

**HP3 (DLR)**
Heat-Flow and Physical Properties Probe

**SEIS (CNES)**
Seismic Experiment for Interior Structure

**APSS (JPL)**
Auxiliary Payload Sensor Suite

**IDS (JPL)**
Instrument Deployment System

**RISE (S/C)**
Rotation and Interior Structure Experiment

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SEIS Overview/Description

SEIS electronics (ETHZ): 10x24 bits + 72x12 bits data logger

SEIS tether, TBK and WTS (JPL)

SEIS LVL (MPS): Levelling platform

CNES: Overall management and integration; Cradle

3 axis SEIS SP (IC)

3 axis SEIS VBB (IPGP)
Environmental noise

- We are here......
Environmental noise

• but would like to be there……

Seismic vault
Environmental noise: installation goals

Planet with Ocean and Atmosphere

Planet without atmosphere and ocean
Temperature and wind protection

Evacuated sphere

Thermal shield

Wind protection

Sealing skirt

Thermo-elastic service loop
### SEIS Expected Natural signals

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Frequency</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>M~5.5</td>
<td>1-2/yr</td>
<td>Global</td>
</tr>
<tr>
<td>M~4.5</td>
<td>~10/</td>
<td>Global to regional</td>
</tr>
<tr>
<td>M~3.5</td>
<td>~100/</td>
<td>regional</td>
</tr>
<tr>
<td></td>
<td>~10-15/</td>
<td>Impacts</td>
</tr>
</tbody>
</table>

- **Thermoelastic cooling**
- **Atmospheric loading**
- **Atmospheric generated seismic noise**

**Phobos tide**
Wind/pressure generated seismic waves and static loading

The atmosphere and wind/pressure fluctuations will be a major source of ground displacement for frequencies > 0.02 Hz with:

1. At long period, static deformations of the surface, associated to wind generated pressure waves (static loading)
2. At short period, dynamic ground acceleration, associated to local and possibly regional subsurface trapped surface waves excited by wind dynamic pressure (short period seismic waves)
3. Again at short period, wind interaction with the shield and the lander (seismic noise)
4. On the global scale and at long period, surface waves excited by the global weather pressure fluctuations (long period seismic waves and normal mode hum)
At 10 sec, the typical expected ground deformation are expected to be $\sim 5$ nm/µbar for 5.7 m/s wind. Sensitivity decrease to 2 nm/µbar for larger wind (deeper sounding) and is 1/f dependent. $10^{-9}$ m s$^{-2}$/Hz$^{1/2}$ ground acceleration is equivalent to 50 mPa/Hz$^{1/2}$ in pressure (at 10 sec).
Environmental sensors for SEIS support

- **Pressure** (10 mPa/Hz\(^{1/2}\) @ 10s barometer; JPL)
- **TWINS** (Temperature and Wind for INSight) – Wind speed and direction, air temperature (REMS-based anemometer and thermal sensors; CAB, Spain)
- **IFG** (Insight FluxGate) – Magnetic field (0.1 nT)
SEIS Expected Natural signals

M~5.5 1-2/yr
Global

M~4.5 ~10/yr
Global to regional

M~3.5 ~100/yr
Regional

Impacts 10-15/yr

Thermoelastic cooling

Seismes
Et
Impacts

Phobos tide

Bonus:
Tectonic activity

Atmospheric loading
Atmospheric generated seismic noise
SEIS Expected Natural signals

- **M~5.5** 1-2/yr Global
- **M~4.5** ~10/ Global to regional
- **M~3.5** ~100/ regional

Impacts: 10-15/yr

- Thermoelastic cooling
- Seismes Et Impacts
- Bonus: Tectonic activity
- Atmospheric loading
  - Atmospheric generated seismic noise

Phobos tide
Estimation \( \sim 5.3 \text{tons} \) at 10 km/s \( \Rightarrow 5 \times 10^7 \) Ns, plus ejecta effects \( \sim 10^8 \) Ns

Seismic record from Apollo 17 SIVB

Apollo 13 SIVB
Estimation \(\sim 5.3\) tons at 10 km/s \(\Rightarrow 5 \times 10^7\) Ns, plus ejecta effects \(\sim 10^8\) Ns
SEIS Expected Quakes...

**Thermoelastic cooling**

- M~5.5 Global: 1-2/yr
- M~4.5 Global to regional: ~ 10/yr
- M~3.5 regional: ~100/yr

**Impacts**
- 10-15/yr

**Phobos tide**

**Bonus:**
- Tectonic activity

**Atmospheric loading**
- Atmospheric generated seismic noise

**Seisms Et Impacts**
Largest quakes: Normal modes

• Normal modes of a $2 \times 10^{17}$ Nm quake
• « spectroscopy » seismology: does not need the knowledge of the source location
• will constrain the upper mantle with the normal modes frequency inversion (e.g. PREM on Earth)
• Might also be excited by the atmospheric turbulences

TUTORIAL EXERCICE 0: WHAT ARE THE TYPICAL NORMAL MODES DIFFERENCES BETWEEN MODELS?
Moderate quakes: Turning waves

Rayleigh

Overtones

Rms Noise in bandwidth

Model

$t_{R1} - t_0 = \frac{\Delta}{v_R}$

$t_{R2} - t_0 = \frac{2\pi a - \Delta}{v_R}$

$t_{R3} - t_{R1} = \frac{2\pi a}{v_R}$

$\frac{\Delta}{\pi a} = 1 - \frac{t_{R2} - t_{R1}}{T_R}$

$t_s - t_p = f_1(\Delta, v_s, v_p)$

$t_R - t_p = f_2(\Delta, v_s, v_p)$

$T_R = f_3(f, v_s, v_p)$
Amplitude of Rayleigh wave trains normalized by R1 amplitude at an epicentral distance of 10,000 km on Earth

Surface waves are one order of magnitude larger on Mars for R2 and R3
And .... the core

- Two ways investigation:
  - non-seismic by detection of the Phobos solid tide (~mm) and interpretation of the amplitude in term of core size
  - seismic by detection of the core reflected waves (ScS) similar Earth and Moon
The ultimate challenge...
Near field: Atmospheric pulse (1)

Rupture wave (2)

Seismic wave (3) and tsunami (4)
Surface waves energy lost?

Atmospheric lost

Solid Earth lost (Q)

Amplitude Conversion

Energy Conversion

Energy balance

\[ t = \frac{2\rho_{\text{int}}c_{\text{int}}}{\rho_{\text{air}}c_{\text{air}} + \rho_{\text{int}}c_{\text{int}}} \approx 2 \]

\[ r = \frac{\rho_{\text{air}}c_{\text{air}} - \rho_{\text{int}}c_{\text{int}}}{\rho_{\text{air}}c_{\text{air}} + \rho_{\text{int}}c_{\text{int}}} \approx -1 \]

\[ T = \frac{\rho_{\text{air}}c_{\text{air}}}{\rho_{\text{int}}c_{\text{int}}} t^2 \]

\[ R = r^2 \]

\[ E = T + T \text{Re} \left( \frac{2\pi}{Q} \right) + \ldots + T \left( \text{Re} \left( \frac{2\pi}{Q} \right) \right)^p + \ldots \]

\[ E = \varepsilon \frac{2Q}{\pi} \frac{\rho_{\text{air}}c_{\text{air}}}{\rho_{\text{int}}c_{\text{int}}} \]
Atmospheric coupling for several planets...

\[ E = T + T \Re \left( \frac{2\pi}{Q} \right) + \ldots + T \left( \Re \left( \frac{2\pi}{Q} \right) \right)^p + \ldots \]

\[ E = \varepsilon \frac{2Q}{\pi} \frac{\rho_{air} c_{air}}{\rho_{int} c_{int}} \]
More on atmosphere-ionosphere physics…

\[
\frac{d\vec{v}_i}{dt} = \frac{eB}{M_i} \left( \frac{\vec{E}}{B} + \vec{v}_i \times \vec{n} \right) - \frac{k_B T \nabla N_i}{M_i N_i} + \vec{g} + v_{in} (\vec{u} - \vec{v}_i)
\]

100 s\(^{-1}\) ~larger term

Can be neglected

1-10 s\(^{-1}\)

Can be neglected

\[
\frac{\partial n}{\partial t} + \text{div}(n\vec{v}_i) = 0
\]

- gravity can be neglected for the time variations

- control of the ion/electrons wind is by the magnetic field diffusion and the neutral-ion collision frequency \(v_{in}\)

- Typical species : \(O_2^+, O^+, NO^+, e^-\)

- This at the end generate a charge (both + and -) flux and density \(n\) perturbations
Detection tools and instruments

- Measure based on the TEC tomography by dense Networks: Dense Networks are more and more available in USA, Japan, Europe
Ionospheric seismic acoustic wave

Tokach-Oki 9/25/2003 M~8.3

Kurils 13/1/2007 M~8.1

Tohoku 3/11/2003 M~9

Kii 9/5/2004 M~7.4

Rolland et al., 2011
Airglow: OI red line

\[ O_2 + O^+ \rightarrow O_2^+ + O \]
\[ O_2^+ + e^- \rightarrow O + O(^1D) \]
\[ O(^1D) \rightarrow O(^3P) + h\nu \]

Chemical reaction

630 nm

Emission peak at 250 km

quiet night 50-100 Rayleigh

about 12.5-25 mWatt/km^2 of light power
• Seismic/tsunami waves generate 0.1-1% more or less exited oxygens, which generate photon to reach 3P level

\[ O_2 + O^+ \rightarrow O_2^+ + O \]
\[ O_2^+ + e^- \rightarrow O + O(1D) \]
\[ O (1D) \rightarrow O (3P) + h\nu \]

• this generates a seismic light of 100-100 microWatt/km^2
The Haida Gwaii tsunami

2012/10/28, Mw 7.8

Rolland et al., in prep

Airglow camera

GPS TEC
New frontiers of Planetary seismology

New data: end 2016

Possible First tsunami space data:
2020 - 2025

Possible return: 2020 - 2025

Old data with new science

More and more data from denser seismic networks

Tutorial Exercise 2:
Imagine seismology on the Moon without seismometers.....