WHAT TO EXPECT OF NETLANDER SEISMIC DATA : REPROCESSING OF APOLLO SEISMIC DATA

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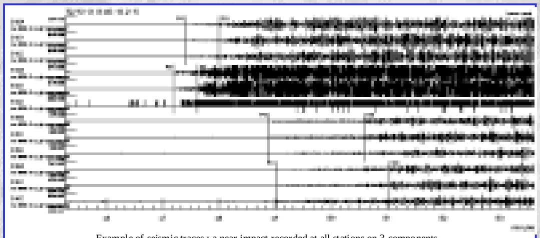
Introduction

The Apollo Seismic network (4 stations) was installed on the near side of the Moon between 1969 and 1972. Recordings stopped in 1977. We expect data provided by the Netlander Seismic Network not to be very different from the Apollo one, in comparison to the data available for the Earth. We show here how we processed the data and what kind of study is feasible with a four stations network. Moreover, our analysis permitted to propose a new seismic velocity model which states a thinner Moon crust than usually assumed.



Example of seismic traces : a near impact recorded at all stations on 3 components

Precedent results

- *Toksöz (1974)*
  - Waveform study of artificial impacts leading to a 60 km thick crust, above a 10 km layer of high P velocity (9km/s).
  - Upper mantle P velocity 8km/s inferred from some deep events.
- *Goins (1981)*
  - Same crust model than Toksöz.
  - Decreasing P and S velocities down to 1000 km deep.
- *Nakamura (1983)*
  - Simplified model of Toksöz for the crust.
  - Negative gradient for both P and S velocities down to 500 km and higher velocities (Vp=8.26 km /s) from 500 to 1000km.

Questions

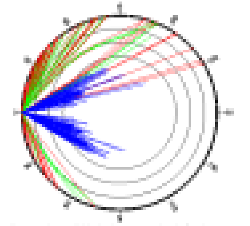
Crust thickness:

- Models have been constructed to match waveforms
- Arrival times are not really consistent

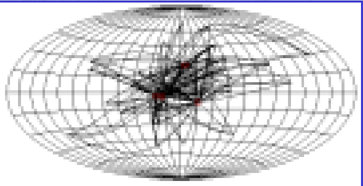
Mantle velocities:

Discrepancies between different models:

- 10 km thick high-velocity layer (*Toksöz*) between crust and mantle.
- Upper mantle velocities compatible in Goins and Nakamura's models.
- Dispersed values for lower mantle velocities.



All ray paths available in the Moon. Blue is for deep events, red for impacts, green for superficial moonquakes.



Ray path of 59 events used for global inversion.

Our results

Our study is focused on two points:

- Crust thickness inverted from arrival time of 19 natural and 8 artificial impacts.

➡the main feature we obtain is a **lunar crust thinner than 30 km**. We can not give strong constraints on interfaces depth but some discontinuities appear around 10 and 25 km. The slow velocity for the first 10 kilometers is the result of fracturation. The base of the crust is around 25 km : the mantle velocity remains stable for P waves (7.75 km/s) below 25 km, and 35 km for S waves (4.6 km/s). The Vp to Vs ratio is high for the subsurface and decreases with depth. This may be the result of deep fracturation which effects are more important for S wave propagation.

- Mantle velocities inverted from the whole data set (27 impacts, 8 superficial and 24 deep moonquakes)

➡The resolution is weak but allows us to note the main features of the velocity distribution, according to the accuracy of the readings of the data set. The P velocity is decreasing from 7.8 km/s in the upper mantle to 7.6 km /s at 700 km deep. An increase of velocity below is possible. The uncertainty is both the result of some incoherence in the data set and of weak redundancy for deep events as there is one more parameter to define.

References
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Lunar Seismology

Seismic propagation features and seismic activity on the Moon *Toksöz et al. (1974)* and *Lammlein et al. (1974)*.

- Seismologic events:
  - Meteoritic and artificial impacts (ascent stage of Lunar Modules and *Saturn* third-stage booster (S4B))
  - Superficial High Frequency Teleseismic Events (thermo-elastic cooling)
  - Deep Events (periodic, thousands of recorded events, localised in 52 focus)
- Seismologic properties:
  - Very low noise level
  - Very weak attenuation on surface
  - High scattering superficial layer

Data processing

All the events reported in the catalogue of Nakamura were inspected, and stacks were performed for deep events, allowing to improve the signal to noise ratio. Their occurrence is actually controlled by tide effects (*Lammlein, 1977*), and for a given location, waveforms are very similar. The identification of seismic phases can be obscured by scattering effects in the first kilometers and also by site effects (station 14) or instrumental problems. The arrival time picking was done with a particular attention devoted to the estimation of uncertainties. This first stage was done without reference to previous readings. Some events were added/removed in our selection comparing to Nakamura's data set (1984). These discrepancies reflect the lack of sufficient undoubtfull data and limit the confidence one may have in the final results.

Model space

The inversion of the velocity structure requires at least the determination of 6 parameters for moonquakes : P and S mean velocities, latitude, longitude, depth and origin time. Only 5 parameters are required for impacts. As the maximum number of data per event is only 8 and often less actually, one cannot expect a detailed description of the velocity structure. The limited extent of the network also limits resolution in depth. So the goal of the present inversion is quite modest : rather than proposing **one** new model, our purpose is more to define **a class** of acceptable models. In this perspective, we operated a **systematic exploration of model space**, a model being defined by a finite number of layers with a set of discrete possible values of P and S velocity and velocity gradient in each layer. We limit the possible models by physical constraints on Vp to Vs ratio, and by prohibiting models with decreasing velocity with depth in the crust.

This operation has been done in **two steps** : an inversion of impact data, looking for information for the **crust**, and a global inversion with all the data, sampling especially the **mantle**.

Inversion

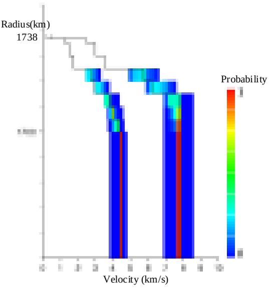
First, the travel time and the horizontal distances in each layer for each velocity value are computed according to the ray parameter value for P and S waves. Then for a given model the suitable values are combined to produce the total travel time and horizontal distance according to the ray parameter and the source depth relocalisation. Finally the total cost function for model *n* can be evaluated by

$$S_n = \frac{1}{2} \Sigma_{i=sources} \; \Sigma_{j=stations} \; \frac{({}_{calc}t_{ijn} - {}_{obs}t_{ij})^2}{\sigma^2_{ij}}$$

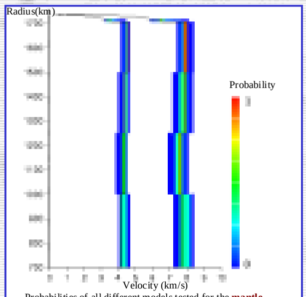
The probability of a given model is defined by

$$P_n = C.\exp\{-S_n\}$$

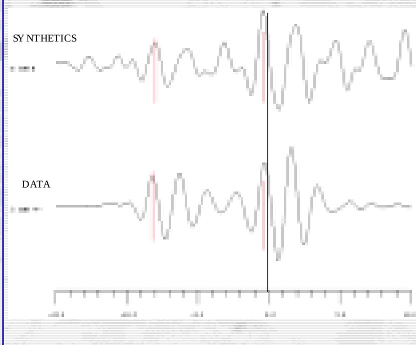
In each layer one can define the probability of a given velocity V as the sum of probabilities of all models with this velocity value in this layer.



Probabilities of all different models tested for the **crust/mantle** interface, resulting of inversion of 27 impacts.



Probabilities of all different models tested for the **mantle**, resulting of inversion of 59 events.



S Receiver function on the Moon

This method developed for the Earth (*Farra and Vinnik, 2000)* highlights seismic conversions which are hidden in the highly scattered coda, and can work with only one station. It consists in isolating the S-waveform and convolving it by the three components. By stacking the vertical component of the 13 events selected on station Apollo 12, we enhance two precursors of the S-wave main arrival : Sp converted waves at bottoms of crust and low-velocity upper layer. We compute synthetic seismograms, processed in the same way than data, for our new model.

Introducing a faster velocity in the first kilometer the synthetic times, arrivals and amplitudes of both precursors fit reasonably the data.