Current knowledge on Moon interior structure from seismology and future challenges by an ISSI international team

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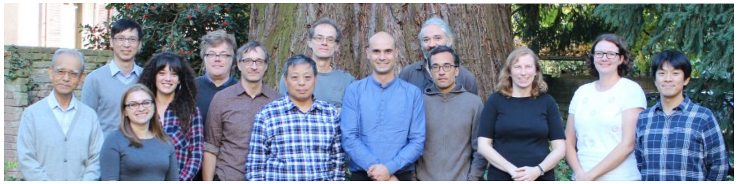

We present here the work performed by an international team on Moon seismology which gathered with the support of ISSI Bern and Beijing. Our goal is to provide to the scientific community the following elements:
- processed data sets and an analysis of their error bars
- internal structure models produced by using these processed data sets and up to date a priori information
- an analysis describing what we know and what we don't know about the internal structure of the Moon, in order to support and drive future seismological deployments

Our team established low level requirements on future geophysical stations deployed on the Moon surface in order to allow these stations to operate as a network even if they are deployed by different missions of different space agencies.
Eventually, we present preliminary inversion tests of the same travel time data set with different methods and model parameters.

Review of internal structure models:

As a first step, we reviewed internal structure models of the Moon and underlying assumptions. Table 1 and Figures 1 and 2 summarize the previous models published and their underlying assumptions.

Model Nickname	TK74	NK83	KM02	LG03	BN06	WB11	GR11	KH14	MS15	Best estimate
Data / prior										
Body wave travel times	P only KV73ab	P+S multiple	P+S NK83	P+S+Smp own+VK01	P+S+Smp LG03+VK01	S only own	P + S LG03	None	P + S LG03	ISSI team data set
Electromag. sounding	None	None	None	None	None	None	None	H83	None	
prior source locations	KV73ab	None	None	None	None	LG03	LG03	None	LG03	
Mass ($\times 10^{22}$ kg)	None	None	None	None	None	None	7.3458	7.3463 ±0.00088	7.34630 ±0.00088	7.34630 ±0.00088
I/MR^2	None	None	None	None	None	None	0.3932 ±0.0002	0.393112 ±0.000012	0.393112 ±0.000012	0.393112 ±0.000012
k_2	None	None	None	None	None	None	0.0213 ±0.0025	0.0232 ±0.00022	0.02422 ±0.00022	0.02277 ±0.00058 (elastic)
h_2	None	None	None	None	None	None	0.039 ±0.008	None	None	0.048 ±0.006
prior crust seismic model	None	None	None	None	None	LG03	LG03	None	None	unknown
prior crust density	None	None	None	None	None	None	2.6-3.0	None	None	2.5-2.6

Table 1: A priori information and data sets used to create the various models presented in figures 1 and 2.

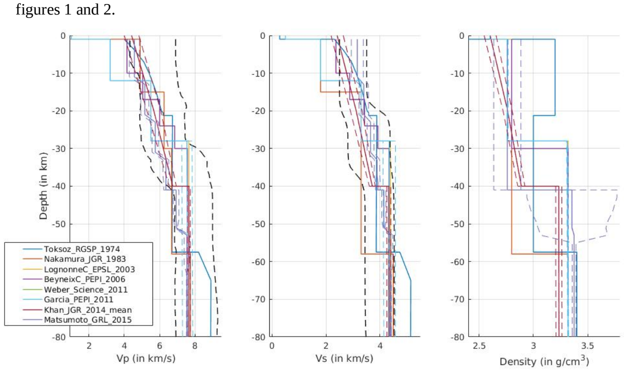

Figure 1: Zoom on the first 80km of the Moon internal structure inferred by various spherically symmetric models. From left to right, P and S wave velocities and density as a function of depth inside the Moon.

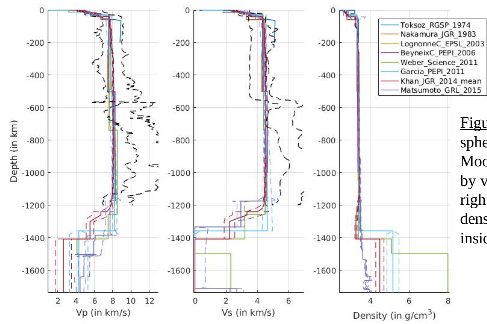

Figure 2: Compilation of spherically symmetric models of Moon internal structure produced by various researchers. From left to right, P and S wave velocities and density as a function of depth inside the Moon.

Previously published models disagree mainly on the inferred crust structure, deep mantle and core. If we exclude the earliest results, there is a general agreement in the top and mid-mantle ranges.

Compilation of body wave arrival time picks:

Our team created a compilation of previously published P and S arrival times for the events with enough arrivals to allow a location.
Deviations relative to median arrival times are presented for surface and shallow events in figure 3, and for S-P times of deep Moon quakes in figure 4.

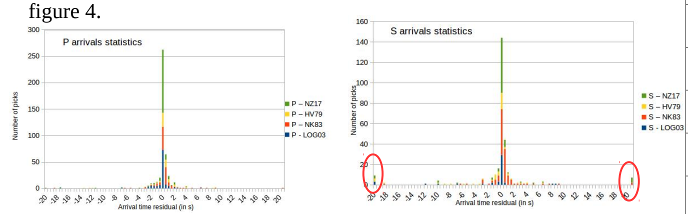

Figure 4: P and S arrival time deviations relative to median value for surface and shallow events

Comparison of deep moonquake stacks

Stacks for deep moonquakes have been created by three different teams over the years of Apollo data processing. Our international team gathered the stack waveforms and started a comparison of these waveforms.

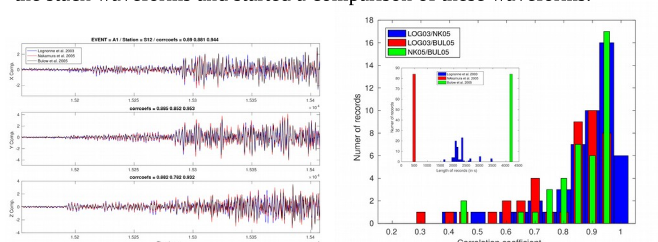

Figure 6: On the left, example of comparison between deep moonquake stacks (event A1, station S12). On the right, statistics of correlation coefficients between the various data sets, and size of records in the various data sets (insert).

Low level requirements on future geophysical station deployments on the Moon by different space agencies:

This requirement flow down has been established in order to fulfill the following level zero requirement:

"Data of geophysical stations deployed on the Moon must allow an international community of researchers to perform network arrival time and waveform analysis."

These requirements are declined into "science requirement" (Level 0), "Station requirements" (level 1) and "Instrument requirements (Level 2):

ILN-REQ-2.1	**Time Accuracy**	Accuracy on the dating of the data samples must be better than one tenth of average sampling rate of the data channel.
ILN-REQ-2.2	**Time Reference**	Data samples must be dated in UTC time.
ILN-REQ-2.3	**Sampling rate**	For a given data channel, data acquisition should be designed to be performed at constant sampling rate in the time reference of the instrument.
ILN-REQ-2.4	**Format**	Data and dataless information must be provided in a format prescribed by FDSN organisation for seismological exchanges.
ILN-REQ-2.5	**Unit**	Data must be provided in units of the international reference system (SI).
ILN-REQ-2.6	**Calibration Information**	The amplitude of the instrument response must be known with an accuracy better than at 10% over the bandpass of the instrument during the entire life of the instrument.
ILN-REQ-2.7	**Calibration Information**	The phase of the instrument response must be known with an accuracy better than at 10° over the bandpass of the instrument during the entire life of the instrument.
ILN-REQ-2.8	**Dataless and processing**	Dataless information must contain a description of all the processing steps from physical unit to digital (count) output of all data channels.
ILN-REQ-2.9	**Compression/ Decompression**	If lossy compression is applied, it should allow signal reconstruction with a accuracy better than 10% of signal energy.
ILN-REQ-2.10	**Aliasing**	The instrument must ensure that less than 0.1% of the signal above Nyquist frequency is aliased in the bandpass of the instrument.
ILN-REQ-2.11	**Noise estimates**	Sensor and instrument noise must be estimated over the bandpass of the instrument and provided in m/s/s/sqrt(Hz) for seismic channels.
ILN-REQ-2.12	**Archiving**	Data and dataless of all the instrument channels must be archived both in planetary databases and in Earth geophysical sensor databases.
ILN-REQ-2.13	**Naming**	A network code and a station code must be ascribed to the geophysical station by FDSN organisation.
ILN-REQ-2.14	**Station location**	The station location must be provided in a standard reference system defined by IAU.
ILN-REQ-2.15	**Station location**	The station location coordinates must be provided with an accuracy lower than 25 meters.
ILN-REQ-2.16	**Axis orientation**	The sensing direction of instrument data channels must be known with an accuracy better than 10 degrees.
ILN-REQ-2.17	**Operations**	Mission, platform and instrument operation activities impacting the signals above instrument noise level must be time stamped, recorded and archived in the dataless information of the instrument.

Conclusions:

- Inferred internal structure models disagree on crust structure, deep mantle and core, because the data are lacking to constrain deep regions.
- Arrival time picks present a low variability (<2 s) except S waves outliers.
- Deep moonquake stacks by various teams present very similar waveforms.

Next steps:

- Invert the same data sets with the same a priori assumptions using different model parametrization to infer resolved and unresolved regions
- Provide body wave arrival time picks and deep moonquake stacks waveforms to the scientific community
- Initiate a core science team for an international lunar seismological network