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► **To cite this version:**

Raphaël Garcia, Jeannine Gagnepain-Beyneix, Sébastien Chevrot, Philippe Lognonné. Very preliminary reference Moon model. *Physics of the Earth and Planetary Interiors*, 2011, 188 (1-2), pp.96-113. 10.1016/j.pepi.2011.06.015 . hal-03964140

**HAL Id: hal-03964140**

**<https://u-paris.hal.science/hal-03964140>**

Submitted on 2 Feb 2023

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# Very Preliminary Reference Moon Model

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## Abstract

The deep structure of the Moon is a missing piece to understand the formation and evolution of the Earth-Moon system. Despite the great amount of information brought by the Apollo passive seismic experiment (ALSEP), the lunar structure below deep moonquakes, which occur around 900 km depth, remains largely unknown. We construct a reference Moon model which incorporates physical constraints, and fits both geodesic (lunar mass and polar moment of inertia, and Love numbers) and seismological (body wave arrivals measured by Apollo network) data. In this model, the core radius is constrained by the detection of S waves reflected from the core. In a first step, for each core radius, a radial model of the lunar interior, including P and S wave velocities and density, is inverted from seismic and geodesic data. In a second step, the core radius is determined from the detection of shear waves reflected on the lunar core by waveform stacking of deep moonquake Apollo records. This detection has been made possible by careful data selection and processing, including a correction of the gain of horizontal sensors based on the principle of energy equipartition inside the coda of lunar seismic records, and a precise alignment of SH waveforms by a non-linear inversion method. The Very Preliminary REference MOON model (VPREMOON) obtained here has a core radius of  $380\pm 40$  km and an average core mass density of  $5200\pm 1000$  kg/m<sup>3</sup>. The large error bars on these estimates are due to the poorly constrained S-wave velocity profile at the base of the mantle and to mislocation errors of deep moonquakes. The detection of horizontally polarized S waves reflected from the core and the absence of detection of vertically polarized S waves favour a liquid state in the outermost part of the

34 core. All these results are consistent, within their error bars, with previous  
35 estimates based on lunar rotation dissipation (Williams et al., 2001) and on  
36 lunar induced magnetic moment (Hood et al., 1999).

37 *Keywords:* Moon, Seismology, Internal Structure, Core, Seismic Body  
38 Waves

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## 39 1. Introduction

40 The radius of Earth's core has been relatively precisely determined more  
41 than one century ago from the analysis of seismic data (Oldham, 1914), only  
42 17 years after the first measurement on a seismogram (von Rebeur-Paschwitz,  
43 1889). But more than 40 years of negative attempts and processing efforts  
44 have been necessary before the publication of the first reported observations  
45 of seismic core phases in the Apollo seismic data (Weber et al., 2011). How-  
46 ever, the results of this pioneering paper in which some inconsistency between  
47 the discontinuity radii deduced from different body waves remains, must be  
48 confirmed by a more precise analysis which integrates the trade-off between  
49 the mantle seismic velocities and the core size, and the constraints on the  
50 body wave amplitudes. Note also that Love numbers were only computed a  
51 posteriori and not integrated in the model inversion. As the radius of the core  
52 is a key parameter for constraining scenarios of Moon formation by a giant  
53 impact (Benz et al., 1989; Canup and Asphaug, 2001), its precise determina-  
54 tion will greatly improve our understanding of the geometry and dynamics  
55 of such giant and catastrophic impact, providing crucial constraints on the  
56 state of primordial Earth's mantle. Prior to Weber et al. (2011), none of the  
57 published seismic models (Toksoz et al., 1974; Nakamura et al., 1976, 1982;  
58 Khan and Mosegaard, 2002; Lognonné et al., 2003; Gagnepain-Beyneix et al.,  
59 2006; Khan et al., 2007) have put direct constraints on the lunar core radius,  
60 and only indirect constraints were achieved. Those come from the observa-  
61 tions of magnetic signals related to the lunar's core magnetic field rejection  
62 (Russell et al., 1982; Hood et al., 1999) and from the inversion of geode-  
63 tic data (Hood and Jones, 1987; Mueller et al., 1988; Kuskov and Kronrod,  
64 1998; Kuskov et al., 2002), including the Love numbers (Williams et al., 2001;  
65 Khan et al., 2004; Khan and Mosegaard, 2005). Among these constraints,  
66 the difference between the spin of the polar axis and the Cassini spin state  
67 measured by Williams et al. (2001) is central for suggesting a liquid core. So  
68 far, the suggested values of this lunar liquid core radius range from 250 km

69 to 450 km.

70 Constraints on the core composition are even much weaker, as the end  
71 member values for its size lead to either pure iron core for the smallest values,  
72 to ilmenite core for the largest ones (see for example Lognonné and Johnson  
73 (2007) for the trade-off of core models verifying both the mantle seismic con-  
74 straints and the global geodetic ones). The seismically inverted temperature  
75 at the bottom of the mantle provided by Gagnepain-Beyneix et al. (2006)  
76 or Khan et al. (2007) are all lower than the pure iron liquidus temperature,  
77 suggesting that some light elements must be present in the core if it is liquid.  
78 These two models however neither include the Love numbers nor core seismic  
79 phases, even though these two types of information could directly constrain  
80 the size of the core in their inversions.

81 In this study, we investigate the seismic structure of the lunar interior fol-  
82 lowing a two-step approach. First, we construct a set of acceptable seismic  
83 models of the Moon constrained by mass, moment of inertia, Love numbers  
84 and arrival times of P and S waves measured by the Apollo passive seismic  
85 experiment. Then, we estimate the core radius by detecting core reflected  
86 S wave arrivals from waveform stacking methods. The final result is a pre-  
87 liminary reference model for the Moon, that includes the size and average  
88 density of the core.

## 89 2. Construction of seismic moon models

90 This section describes the construction and selection of the best radial  
91 seismic lunar models. These models are described by a small number of pa-  
92 rameters, respecting a set of a priori geophysical equations and fitting seis-  
93 mological and geodesic observations. The aim is to obtain the best physical  
94 models for each core radius and use them to detect core reflected phases.

### 95 2.1. *A priori information*

96 The radial models are constructed in order to fit exactly the lunar mass  
97  $M_o = 7.3458 \times 10^{22}$  kg (Konopliv et al., 2001; Goossens and Matsumoto,  
98 2008). The crustal model is extracted from Gagnepain-Beyneix et al. (2006)  
99 seismic model (see figure 1). Crustal density ( $\rho_c$ ) below the 1 km thick re-  
100 golith layer is assumed to be constant and allowed to vary in order to fit  
101 geodesic observations. The strong degree one crustal thickness variation is  
102 taken into account by assuming a Moho depth of 28 km below the Apollo  
103 network (on the near side) in order to fit seismic observations, and an average

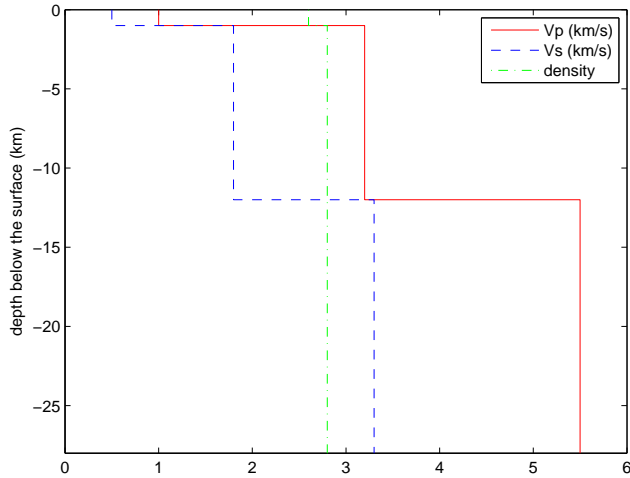


Figure 1: A priori crust model extracted from Gagnepain-Beyneix et al. (2006) assuming a constant density inside the crust below the 1 km thick regolith layer.

104 Moho depth of 40 km (Chenet et al., 2006) in order to fit geodesic observa-  
 105 tions. Studies of lunar gravity and topography constrain both the average  
 106 crustal thickness and the density contrast between the crust and the mantle.  
 107 However, these parameters are correlated. Assuming an average Moho depth  
 108 of 40 km, the density contrast between crust and mantle is predicted to be  
 109 about 0.55 (Chenet et al., 2006; Wiczorek et al., 2006). This value is taken  
 110 as an a priori for the construction of the radial Moon models.

111 The lunar mantle is assumed to be homogeneous and without any phase  
 112 transition. This assumption is strong, but if the composition of the lunar  
 113 mantle is close to Earth’s mantle, no phase change of major silicate con-  
 114 stituents is expected in the pressure and temperature ranges of the Moon  
 115 mantle. In addition, previous investigations of lunar mantle chemistry based  
 116 on seismic data did not detect any strong chemical composition variation  
 117 with depth (Khan et al., 2007), suggesting that the 550 km depth discon-  
 118 tinuity, reported in earlier models (Nakamura, 1983; Khan and Mosegaard,  
 119 2002), is weakly resolved by the Apollo data set (Lognonné and Johnson,  
 120 2007). In addition, we assume an adiabatic temperature gradient in the lu-  
 121 nar mantle. Even if not fully valid in the middle and upper mantle, where the  
 122 temperature profile is mainly conductive (Gagnepain-Beyneix et al., 2006),

123 the adiabatic hypothesis is expected to generate no more than a few percent  
 124 of differences in seismic velocities (Bina, 2003) which is smaller than the typ-  
 125 ical error of lunar seismic models. Assuming homogeneity and adiabaticity  
 126 of the lunar mantle, we can use the Adams-Williamson equation to derive  
 127 the density profile of the Moon mantle:

$$\frac{d\rho}{dr} = -\frac{\rho(r)g(r)}{\Phi(r)} \quad (1)$$

128 where  $r$  is the radius,  $\rho(r)$  the volumic mass,  $g(r)$  gravity, and  $\Phi(r)$  the  
 129 seismic parameter given by:

$$\Phi(r) = V_P^2(r) - \frac{4}{3}V_S^2(r) \quad (2)$$

130 where  $V_P(r)$  and  $V_S(r)$  are respectively the P and S wave velocities. If we  
 131 assume a state of hydrostatic equilibrium for the lunar interior, pressure  
 132 variations are described by:

$$\frac{dP}{dr} = -\rho(r)g(r) \quad (3)$$

133 where  $P(r)$  is pressure.

134 Consequently, if seismic velocities are known, the above equations can be  
 135 integrated from top to bottom in order to construct gravity, pressure, and  
 136 density profiles, using the additional relation between gravity and density:

$$g(r) = \left(\frac{r_o}{r}\right)^2 g_o - \frac{4\pi G}{r_o^2} \left(\frac{r_o}{r}\right)^2 \int_r^{r_o} \rho(u)u^2 du \quad (4)$$

137 where  $G$  is the gravitational constant,  $r_o$  the average Moon radius (1737.1  
 138 km) and  $g_o = \frac{GM_o}{r_o^2}$  the surface gravity. This procedure has been used since the  
 139 early sixties in order to produce density models of Earth's interior assuming  
 140 a starting value of density  $\rho_o$  (Alterman et al., 1959).

141 In order to link seismic wave velocities to density, a Birch law (Birch, 1964)  
 142 is used:

$$V_P(r) = a + b\rho(r) \quad (5)$$

143 where  $a$  and  $b$  are assumed to be constant because the mantle is assumed to  
 144 be homogeneous. In addition, because the P-wave to S-wave velocity ratio  
 145 increases with depth in previous Moon seismic models (Nakamura et al., 1982;

146 Khan and Mosegaard, 2002; Lognonné et al., 2003; Gagnepain-Beyneix et al.,  
 147 2006), it is assumed to vary linearly with radius according to:

$$\frac{V_P(r)}{V_S(r)} = A + Br \quad (6)$$

148 For given values of density at the top of the mantle ( $= \rho_c + 0.55$ ), Birch law  
 149 parameters ( $a$  and  $b$ ), and P to S velocity ratio parameters ( $A$  and  $B$ ), a seis-  
 150 mic model of the mantle predicting  $V_P(r)$ ,  $V_S(r)$  and  $\rho(r)$  can be constructed  
 151 down to the core.

152 For a given value of core radius ( $R_{core}$ ), and using the lunar Mass, the average  
 153 core density ( $\rho_{core}$ ) is deduced.

154

155 The procedure described above allows us to build seismic and density  
 156 profiles of the lunar interior obeying simple physical laws with only 6 pa-  
 157 rameters: crust density ( $\rho_c$ ), Birch law parameters ( $a$  and  $b$ ), P to S veloc-  
 158 ity ratio parameters ( $A$  and  $B$ ) inside the mantle, and core radius ( $R_{core}$ ).  
 159 These parameters are gathered in a model vector  $\mathbf{m}$ . Average core density  
 160 is computed in order to fit exactly the mass of the Moon. Only models with  
 161 core density in the range  $[4.0-10.0]$  kg/cm<sup>3</sup>, and fitting both Love numbers  
 162  $k_2=0.0213\pm 0.0025$  and  $h_2=0.039\pm 0.008$  (Williams, 2007; Goossens and Mat-  
 163 sumoto, 2008) and polar moment of inertia ratio  $IR=0.3932\pm 0.0002$  (Kono-  
 164 pliv et al., 2001) within their error bars will be selected.

165 In order to construct physical Moon models, the 6 parameters are explored  
 166 following ranges and steps given in table 1. The range of crustal density ( $\rho_c$ )  
 167 is defined according to previous estimates (Gagnepain-Beyneix et al., 2006;  
 168 Chenet et al., 2006). Birch law parameters are explored between values cor-  
 169 responding to the Earth upper mantle as defined in PREM ( $a = -7.4146$  and  
 170  $b = 4.5872$ ) (Dziewonski and Anderson, 1981) and IASP91 ( $a = -10.7346$   
 171 and  $b = 5.5743$ ) (Kennett and Engdahl, 1991) reference Earth models. P  
 172 wave to S wave velocity ratio is explored around the value obtained for a  
 173 Poisson solid ( $\sqrt{3} \approx 1.73$ ). The ranges for origin ( $A$ ) and slope ( $B$ ) of its  
 174 variation with radius are chosen in order to allow either decrease or increase  
 175 with depth, and variations around values obtained in previous models. Core  
 176 radius is explored from 250 km to 490 km.

Table 1: Summary of parameter ranges explored in the construction of physical Moon models.

Parameter	Range	Step
Crust density (kg/cm <sup>3</sup> ) ( $\rho_c$ )	[2.6 3.0]	-
Birch law origin ( $a$ )	[-10.74 -7.41]	-
Birch law slope ( $b$ )	[4.58 5.57]	-
$\frac{V_P}{V_S}$ law origin ( $A$ )	[1.0 2.95]	-
$\frac{V_P}{V_S}$ law slope (km <sup>-1</sup> ) ( $B$ )	[-0.000662 0.0004]	-
Core radius (km) ( $R_{core}$ )	[250 490]	5

177 *2.2. Best radial Moon models*

178 The next step is to select the best radial Moon models that fit both P  
179 and S arrival times and geodesic observations. In order to let the core radius  
180 as a free parameter, a best radial Moon model will be obtained for each core  
181 radius.

182 Then, for each core radius, an exploration of the five remaining parameters  
183 is performed with a Neighbourhood Algorithm (NA) (Sambridge, 1999) with  
184 ten randomly selected starting models and performing twelve iterations of  
185 NA with parameters ns=30 and nr=3. These parameters mean that at each  
186 iteration the neighbourhoods of the three best models are explored with 10  
187 new random models. The cost function to minimize is defined as the sum of  
188  $\chi^2$  functions of seismic travel times and geodesic observations (Love numbers  
189 and polar moment of inertia ratio):

$$J(\mathbf{m}) = \frac{1}{N_s} \sum_i^{N_s} \frac{(t_i^{obs} - t_i^{calc})^2}{\sigma_i^2} + \frac{1}{3} \left( \frac{(h_2^{obs} - h_2^{calc})^2}{\sigma_{h_2}^2} + \frac{(k_2^{obs} - k_2^{calc})^2}{\sigma_{k_2}^2} + \frac{(IR^{obs} - IR^{calc})^2}{\sigma_{IR}^2} \right) \quad (7)$$

190 with  $t_i^{obs}$  the observed travel time of the seismic phase (including both P and  
191 S phases),  $t_i^{calc}$  the predicted travel time inside model  $\mathbf{m}$ ,  $\sigma_i^2$  the travel time  
192 error,  $N_s$  the number of travel time measurements; and  $h_2^{obs}$ ,  $h_2^{calc}$ ,  $k_2^{obs}$ ,  $k_2^{calc}$ ,  
193  $IR^{obs}$ ,  $IR^{calc}$ ,  $\sigma_{h_2}$ ,  $\sigma_{k_2}$  and  $\sigma_{IR}$  respectively observed and calculated values  
194 of  $h_2$  and  $k_2$  Love numbers, polar moment of inertia ratio and corresponding  
195 errors. The first part of the right hand side of equation (7) will be referred  
196 to as  $\chi_{seismo}^2$ , whereas the second part as  $\chi_{geod}^2$ . This cost function gives an



197 equal weight to seismological and geodetic observations in order to construct  
198 a reference model constraining both density and seismic velocities.

199 The  $h_2^{calc}$ ,  $k_2^{calc}$  and  $IR^{calc}$  values are computed during model construction.  
200 However, in order to be fully consistent, the computation of  $\chi_{seismo}^2$  requires  
201 relocation of all natural seismic events, and correction for P and S wave shal-  
202 low structure below the seismic stations. Therefore, for each physical model  
203 tested, the P and S wave traveltimes given by Lognonné et al. (2003) are  
204 inverted in order to relocate the events and to obtain P and S wave sta-  
205 tion corrections of zero average. Only arrival time data with errors smaller  
206 than 10 s are kept. A total of 343 P and S travel times from 64 events (8  
207 artificial impacts, 19 meteor impacts, 10 shallow events and 27 deep moon-  
208 quakes) are used. The inversion is performed with a damped Gauss-Newton  
209 algorithm (Tarantola, 1987) with starting event location parameters given by  
210 Gagnepain-Beyneix et al. (2006) and zero station corrections. The  $\chi_{seismo}^2$   
211 value of P and S wave travel times obtained after inversion is computed for  
212 each physical model tested.

213 Results of the inversion are summarized in figures 2, 3 and 4. Figure 2 gives  
214 an example of the parameter space sampling by NA algorithm for a core ra-  
215 dius of 380 km. The sampling by NA algorithm concentrates around a single  
216 minimum value inside the volume of parameter space explored. Figure 3a  
217 plots the minimum values of the cost function  $J(\mathbf{m})$ ,  $\chi_{geod}^2$  and  $\chi_{seismo}^2$  ob-  
218 tained for each core radius. The best models for core radius between 300 km  
219 and 400 km give a similar fit of the seismological and geodesic observations.  
220 For core radius smaller than 300 km, the fit of seismological observations is  
221 slightly degraded. For core radius larger than 400 km,  $\chi_{geod}^2$  at minimum  
222 value of the cost function increases with radius, reflecting the difficulty to  
223 fit geodesic observations with large core radii. Figure 3b plots the variation  
224 with radius of the P and S wave velocities and density for the best mod-  
225 els obtained for each core radius. A comparison with the starting model of  
226 Gagnepain-Beyneix et al. (2006) shows that the fit of geodesic observations  
227 favours S wave velocities at the bottom of the mantle higher than previously  
228 inferred. Figure 4 presents the correlation between parameters obtained for  
229 the best radial models. Birch law parameters are strongly correlated be-  
230 tween themselves, but not with core radius.  $\frac{V_P}{V_S}$  ratio presents an increase  
231 with depth consistent with previous investigations. The parameters describ-  
232 ing the variations of  $\frac{V_P}{V_S}$  ratio are correlated between themselves, but there  
233 is no significant correlation with core radius. The crust density is almost  
234 constant around 2.76 kg/cm<sup>3</sup>. It means that, despite large variations of

235 Birch law parameters, imposing the average crustal thickness (40 km) and  
236 the density jump at the crust/mantle interface ( $0.55 \text{ kg/cm}^3$ ) strongly con-  
237 strains the average crust density in a radial model consistent with geodesic  
238 observations. However, an average crust density of  $2.76 \text{ kg/cm}^3$  is consistent  
239 with our assumptions and with previous estimates (Chenet et al., 2006). The  
240 core density is correlated with core radius with high densities for small core  
241 sizes and low densities for large core sizes. Overall, geodesic and travel time  
242 data poorly constrain the size of the core, which motivated us to look for  
243 additional constraints that could come from core reflected phases.

### 244 **3. Modelling core reflected phases**

245 This section demonstrates that the core radius can be constrained by the  
246 detection of horizontally polarized S waves reflected on the core (ScSH) and  
247 precise the data set that can be used for such a detection. The data and  
248 signal processing methods allowing ScSH wave detections are described in  
249 the next section.

#### 250 *3.1. Waveform modelling*

251 We focus on SH waves reflected on the core because, if the upper part  
252 of the lunar core is fluid (Williams et al., 2001), their energy is completely  
253 reflected back to the surface. Ray theoretical amplitudes of body waves are  
254 computed including geometrical spreading and attenuation (see last table of  
255 the paper for values of quality factor). As shown in figure 5a, ScSH am-  
256 plitude at the recording station is of the order of 10 to 20% of the direct  
257 SH wave amplitude depending on the attenuation model and assuming sim-  
258 ilar amplitudes radiated at the source. Deep moonquakes with best signal  
259 to noise ratio (mainly A01, A06 and A07 events) are assumed to be driven  
260 by tides (Cheng and Toksoz, 1978; Araki, 2001). A recent analysis of the  
261 focal mechanism of these events, which is based on a model that fits only  
262 occurrence times of the events, suggests fault plane orientations with a dip  
263 angle between  $60^\circ$  and  $70^\circ$  with large error bars (Weber et al., 2009). How-  
264 ever, studies of these events based only on observations of P and S wave  
265 amplitudes and polarities favour focal mechanisms with a horizontal focal  
266 plane (Nakamura, 1978; Koyama and Nakamura, 1980). As shown in figure  
267 5b, these focal mechanisms have a maximum of SH energy radiated along  
268 the vertical direction, which correspond to the take-off angles of ScSH wave.

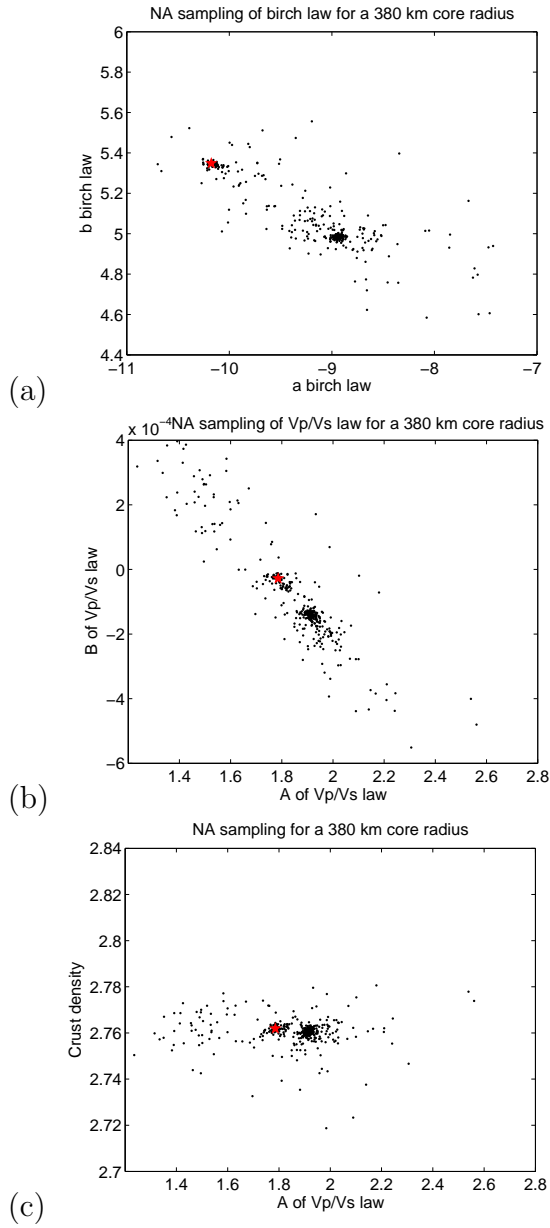


Figure 2: Example of parameter space sampling by NA algorithm for a core radius of 380 km. (a) sampling projected into the plane of  $a$  and  $b$  Birch law parameters. (b) sampling projected into the plane of  $A$  and  $B$  parameters of the  $\frac{V_p}{V_s}$  ratio law. (c) sampling projected into the plane of  $A$  and  $\rho_c$  parameters. Each dot represents a model vector and best model values are indicated by a red star.

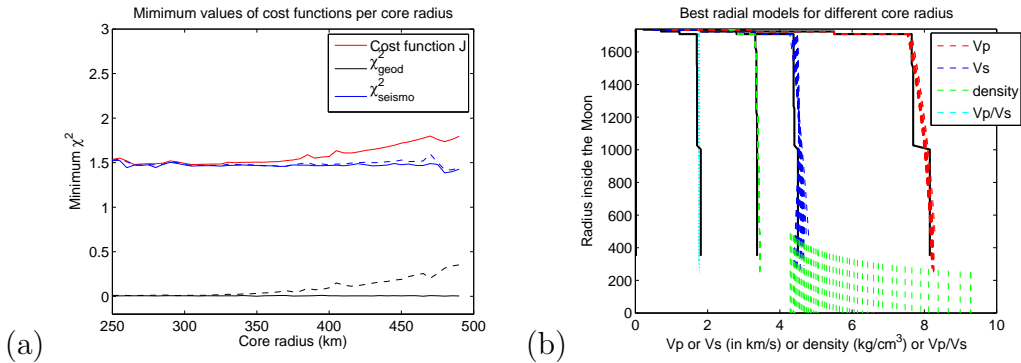


Figure 3: (a) Minimum values of cost function  $J(\mathbf{m})$  (in red),  $\chi_{geod}^2$  (in black) and  $\chi_{seismo}^2$  (in blue) obtained for each core radius. Values of  $\chi_{geod}^2$  (black dashed line) and  $\chi_{seismo}^2$  (blue dashed line) corresponding to minimum values of the cost function  $J(\mathbf{m})$  are also plotted. (b) P-wave (in red) and S-wave (in blue) velocities (in km/s), density (in green) and  $\frac{V_p}{V_s}$  ratio (light blue) of the best models obtained for each core radius (dashed lines). The model of Gagnepain-Beyneix et al. (2006) is plotted as plain black lines for comparison.

269 In contrast, direct SH waves have a smaller excitation at the source. Conse-  
 270 quently, for such source mechanisms, the ScSH/SH amplitude ratio is close  
 271 to one in the 50°-80° epicentral distance range. Moreover, those mechanisms  
 272 generate SH wave and ScSH wave of opposite polarities at the source. Due  
 273 to the change in polarity resulting from reflection at the core surface, these  
 274 two body waves should thus have the same waveform. This waveform sim-  
 275 ilarity can also be used as a posterior constraint to validate the ScSH wave  
 276 detection.

277 In contrast, vertically polarized S waves will lose part of their energy when  
 278 reflected at the core surface due to conversion into P waves reflected and  
 279 transmitted at this interface. Smaller amplitudes for ScSV waves than for  
 280 ScSH waves are thus expected, as observed on Earth.

### 281 3.2. Error propagation

282 The deep moonquake records present a low signal to noise ratio. Records  
 283 allowing P and S arrival detections are obtained only after stacking many in-  
 284 dividual records from the same deep moonquake cluster. Owing to this low  
 285 signal to noise ratio, to the low number of stations, and to the uncertainty on  
 286 the radial seismic model, the error bar on the event location coordinates are  
 287 usually quite large (see table 2). In order to minimize the effect of mislocation  
 288 errors and seismic structure just below the stations, ScS-S differential times

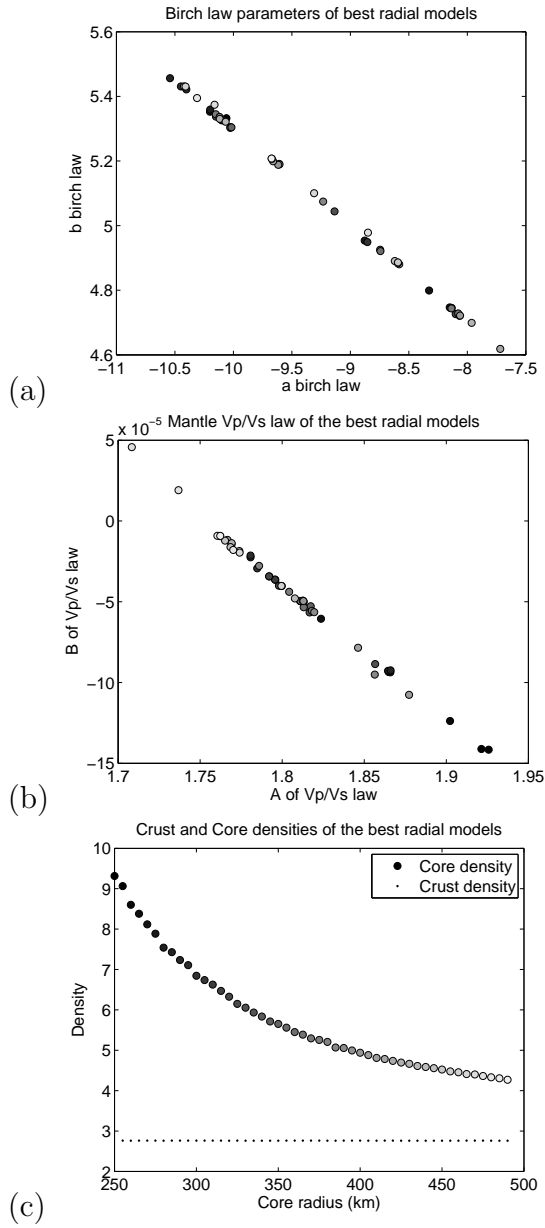
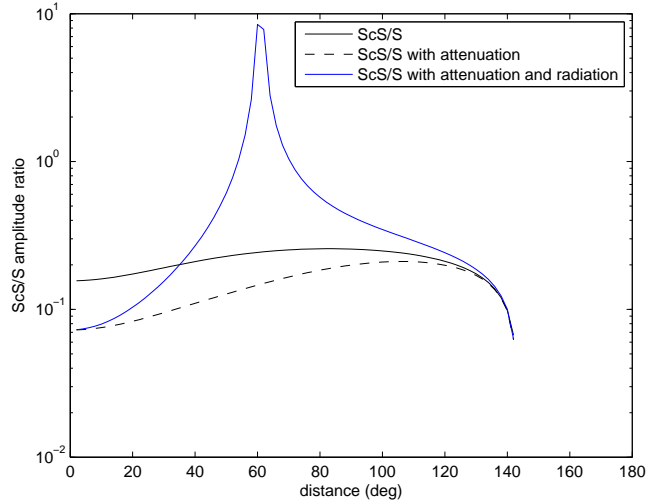
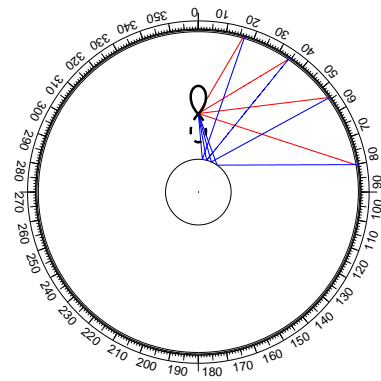


Figure 4: Correlations between parameters when considering the best radial models. (a) best values of  $a$  and  $b$  Birch law parameters. (b) best values of  $A$  and  $B$  parameters of  $\frac{V_p}{V_s}$  ratio law. (c) crust and core densities as a function of core radius (in km) for the best radial models. Color scale of circles goes from black to white with increasing core radius parameter.



(a)

S and ScS rays, SH radiation



(b)

Figure 5: (a) ScS/S amplitude ratio without (plain line) and with (dashed line) attenuation, assuming same radiation pattern at the source; and with attenuation and radiation from an horizontal fault plane (blue line). Computations are performed in the seismic model of Gagnepain-Beyneix et al. (2006) with an S wave quality factor of 300 below 770 km depth. (b) examples of S (in red) and ScS (in blue) ray paths for a 900 km depth event. The radiation pattern (in black) of SH waves for a displacement perpendicular to the figure along an horizontal fault plane is surperimposed, with plain line for positive values, and dashed line for negative values.

289 are used. These differential times present a low sensitivity to the structure  
 290 below the station because S and ScS waves have similar crustal delays. In  
 291 addition, these differential times also present a low sensitivity to event mislo-  
 292 cations along latitude and longitude coordinates, even if, as we will see below,  
 293 this sensitivity is non-zero. Because the largest error is on the quake depth,  
 294 and because this parameter is strongly influencing the ScS-S differential time  
 295 (hereafter called  $t_d$ ), the event depth will be determined simultaneously with  
 296 the core radius. However, ScS-S differential times alone do not allow us to  
 297 relocate the lateral position of the event. Therefore, the stacking process can  
 298 be effective only if the errors on latitude and longitude of the events generate  
 299 relative ScS-S differential time variations between stations smaller than half  
 300 the dominant period of the records, in order to ensure coherent (in phase)  
 301 stack of the body waves. The differential time ScS-S at one station for an  
 302 event location different from the theoretical one may be written:

$$t_d^j(\theta_0 + \delta\theta, \phi_0 + \delta\phi) = t_d^j(\theta_0, \phi_0) + \Delta t_d + \delta t_d^j \quad (8)$$

303 where  $(\theta_0, \phi_0)$  are the (latitude, longitude) theoretical coordinates of the event,  
 304  $\Delta t_d = \frac{1}{N} \sum_j^N (t_d^j(\theta_0 + \delta\theta, \phi_0 + \delta\phi) - t_d^j(\theta_0, \phi_0))$  is the average differential time  
 305 shift residual over all the stations due to the event mislocation, and  $\delta t_d^j =$   
 306  $t_d^j(\theta_0 + \delta\theta, \phi_0 + \delta\phi) - t_d^j(\theta_0, \phi_0) - \Delta t_d$  is the differential time shift residual of  
 307 station  $j$  relative to this average. The second term on the right hand side  
 308 produces a shift of all the ScS-S differential times that is displacing the ScS  
 309 stack relative to its theoretical position, whereas the last term on the right  
 310 hand side produces relative shift between the stations that may generate  
 311 incoherent stacks if it is larger than half the dominant period of the body  
 312 wave. The relative ScS-S differential time variations between stations  $i$  and  $j$   
 313 is defined by  $R\delta t_d^{ij} = \delta t_d^i - \delta t_d^j$ . Table 2 presents an estimate of the maximum  
 314 values ( $\text{Max}(R\delta t_d^{ij})$ ) and standard deviations ( $\text{Std}(R\delta t_d^{ij})$ ) of relative ScS-S  
 315 differential time variations between stations inside the one standard devia-  
 316 tion error ellipse of event positions. These values are controlled by the error  
 317 on the event location, but also by the event position relative to the stations.  
 318 When the back azimuth of the event is approximately the same for all the  
 319 stations (event outside the network area),  $\Delta t_d$  may be large, but  $R\delta t_d^{ij}$  values  
 320 remain small. In contrast, for an event located in the middle of the network,  
 321  $\Delta t_d$  is small, but  $R\delta t_d^{ij}$  values present large variations.

Table 2: Summary of data used in this study. Parameters are the following: latitude, longitude and depth of the quake, and corresponding errors (Gagnepain-Beyneix et al., 2006), initial number of stations available, number of stations selected after removing bad quality records, parameters  $\text{Max}(R\delta t_d^{ij})$  and  $\text{Std}(R\delta t_d^{ij})$ .

Event Name	Lat. (deg)	Long. (deg)	Depth (km)	$\Delta\text{lat.}$ (deg)	$\Delta\text{lon.}$ (deg)	$\Delta\text{depth}$ (km)	Init. # stat.	# stat. sel.	$\text{Max}(R\delta t_d^{ij})$ (s)	$\text{Std}(R\delta t_d^{ij})$ (s)
A01	-17,44	-38,37	917	1,1	0,6	11	4	4	1,82	1,1
A05	-31,04	-44,92	902	3	3	80	2	2	1,34	-
A06	49,7	54,69	860	1	0,7	11	4	4	1,57	0,9
A07	23,97	53,7	900	0,8	0,7	12	4	4	1	0,94
A08	-27,97	-28,08	940	2	1,2	21	1	1	-	-
A09	-37,8	-30,85	975	4	2,6	43	3	2	8,56	-
A10	34,01	-28,04	1139	3	3	80	2	2	0,57	-
A11	9,6	19,49	1233	0,8	0,7	12	3	2	0,73	-
A14	-28,7	-33,94	880	1,7	1,3	22	3	2	4,34	-
A15	-0,94	-2,96	885	3	3	80	3	3	13,39	8,8
A16	6,79	5,14	1105	1,2	0,7	18	3	3	2,26	1,55
A17	23,08	-17,97	861	2,6	0,4	15	3	3	7,51	5,27
A18	18,56	34,72	882	1,8	0,9	24	3	2	3,4	-
A19	15,96	37,91	841	3	3	80	3	2	9,46	-
A20	21,72	-41,01	1055	2,4	0,8	13	3	3	4,32	2,83
A21	-15,8	-43,49	1060	3	3	80	2	1	-	-
A24	-36,85	-38,9	980	2,1	1,7	32	4	3	4,91	2,49
A25	34,4	59,3	898	2	1,7	26	4	4	2,57	2,1
A26	12,19	10,22	1135	1,5	0,7	20	3	2	1,5	-
A27	22,51	18,53	1059	1,9	1,4	14	4	2	3,49	-
A28	32,69	11,64	720	3	3	80	3	1	-	-
A30	11,78	-34,26	921	1,5	1	23	4	4	1,87	2,03
A33	6,89	117,75	887	1,5	1,3	30	3	2	0,46	-
A34	7,04	-9,28	932	1,2	0,6	26	3	3	3,8	2,58
A41	13,9	-26,79	953	5,6	2,2	84	3	1	-	0
A42	22,68	-53,46	1004	1,8	1,4	24	3	2	3,94	-
A44	51,85	57,08	956	5,8	1,9	20	3	3	1,98	0,78

322 Owing to the instrument response of Apollo stations, the largest dominant  
323 period ensuring a good signal to noise ratio is about 2.5 s. Therefore, the only  
324 events for which the stacking process is expected to work properly according  
325 to the error on lateral event coordinates are events A01, A06, A07 and A44.  
326 In addition, detection by stacking process is more reliable if 4 stations are  
327 available. Consequently, only deep moonquake stacks for events A01, A06  
328 and A07 can possibly allow ScSH reliable detections.

#### 329 4. Data and methods

330 This section describes the data and method used to detect SH waves  
331 reflected from the lunar core surface. First, the stacking process of individual  
332 deep moonquake records along X and Y horizontal sensors is described. Then,  
333 a new method, based on the energy equipartition inside the coda waves, is  
334 applied to correct for relative gain variation between X and Y horizontal  
335 sensors. In addition the site response below the station is corrected, and  
336 data are filtered in the frequency range with highest signal to noise ratio.  
337 Finally, the stacking process is described, and bootstrap validations of the



338 results are presented.

#### 339 *4.1. Stacks of deep moonquake individual records*

340 Individual records of deep moonquakes are first aligned by cross-correlation  
341 of the vertical component and the horizontal component with the best S/N  
342 ratio. The part of the individual records presenting spikes have been removed  
343 by hand from the stacks. As a result, the number of individual records stacked  
344 varies with time along the stack. However this method is probably the best  
345 one to ensure that no biases are introduced by a spike correction method.  
346 The number of individual records stacked depends on the seismic station and  
347 on the deep moonquake nest. This number is usually comprised between 20  
348 and 100. An example of deep moonquake stack is presented in figure 6 which  
349 shows the stacks of deep moonquake cluster A01 on the vertical component  
350 of Apollo 12 station.

#### 351 *4.2. Correction of the gain of horizontal sensors*

352 The horizontal components of ground velocity are recorded by two dif-  
353 ferent sensors (X and Y) of Apollo LP seismometers. Because these sensors  
354 may have slightly different gains, the rotation of X and Y components in  
355 order to reconstruct radial and transverse components may be biased. In  
356 order to correct for this effect, X/Y amplitude ratios were computed for each  
357 station in the coda of seismic events with high signal to noise ratios. Be-  
358 cause of the high level of seismic scattering in the lunar crust, the seismic  
359 wavefield in the coda of lunar quakes is approximately in equipartition state  
360 (Larose et al., 2005; Sens-Schönfelder and Larose, 2008). Thus, if the gains  
361 of the two sensors were identical, and assuming only radial variations of seis-  
362 mic scattering properties, we should observe the same energy level on the  
363 two horizontal components (Margerin et al., 2009), and the X/Y ratio in  
364 the coda should be equal to one. If not, the X/Y ratio gives an estimate  
365 of the gain ratio of the two sensors. A limitation to this analysis is a small  
366 correlation between the horizontal components of the Apollo 12 seismometer  
367 discovered by Vinnik et al. (2001). However, this study also indicates that  
368 this correlation is not observed on the other Apollo stations. Figure 7 gives  
369 an estimate of the X/Y ratio for the different stations measured in the coda  
370 of different seismic events. The coda signal is defined here by the part of  
371 the records starting at least 100 s after the S wave arrival. The X/Y ratio is  
372 estimated by different methods (see legend of figure 7), and it presents only  
373 small variations as a function of time inside the coda. For stations S12 and

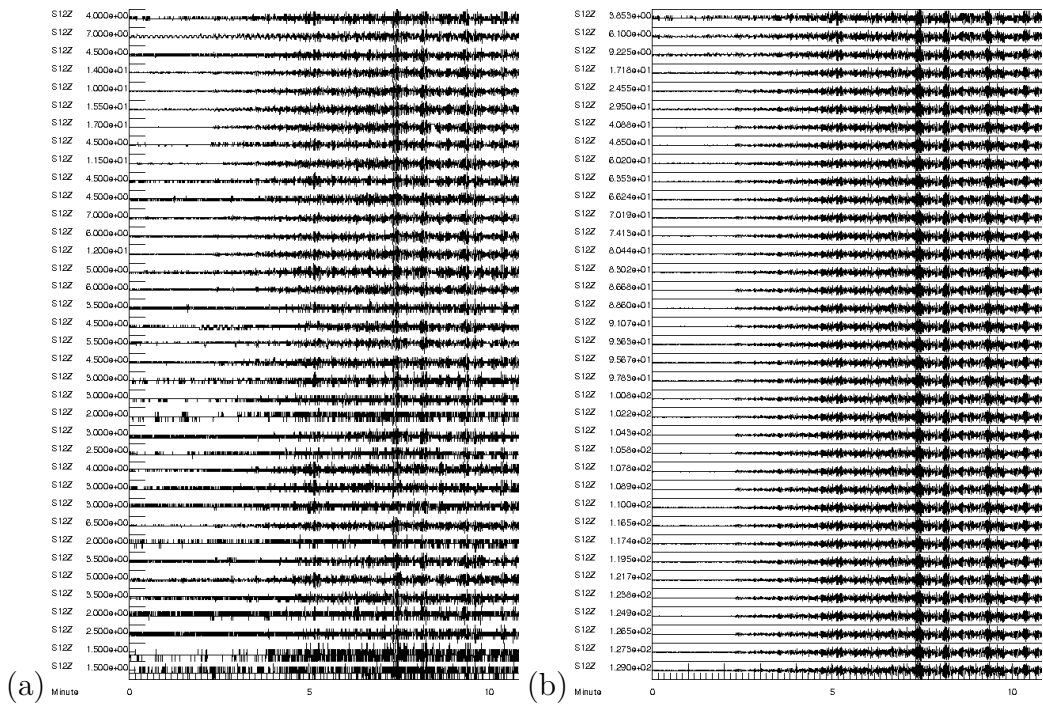


Figure 6: (a) examples of individual records of events belonging to deep moonquake cluster A01 and recorded on the vertical component of station Apollo 12 after alignment by cross-correlation. (b) evolution of the stack as a function of the number of records stacked. From top to bottom each line includes a new record in the stack. The numbers on the left of each trace give the maximum amplitude of the trace expressed in Apollo digital units.

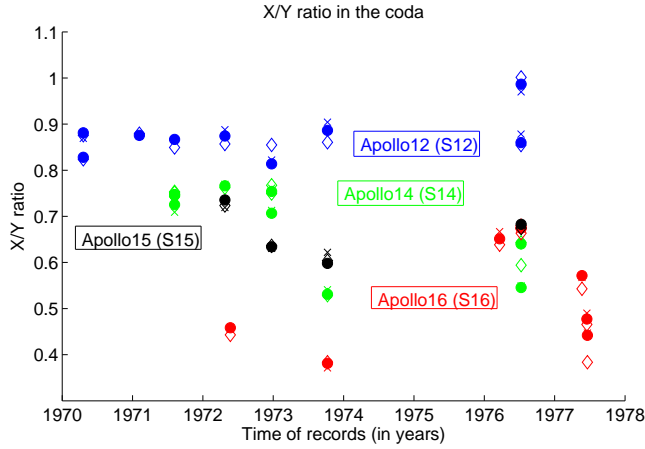


Figure 7: X/Y amplitude ratios in the coda of different seismic events as a function of event origin time (in years). Event origin times after 1973 correspond to deep moonquakes. X/Y ratios are computed with different methods: time average of X/Y logarithm (filled circles), median of X/Y logarithm (crosses) and signal energy ratio (open diamonds). The average X/Y ratios are  $0.856 \pm 0.012$ ,  $0.748 \pm 0.010$ ,  $0.661 \pm 0.035$ ,  $0.533 \pm 0.044$  respectively for seismic stations S12 (in blue), S14 (in green), S15 (in black) and S16 (in red).

374 S14, the codas of artificial impacts created by Lunar modules and stage IV  
 375 of Saturn V rocket were used because of high signal to noise ratio for these  
 376 events. For stations S15 and S16, deep moonquake codas with high signal  
 377 to noise ratios were added to artificial impacts. The X/Y ratio of different  
 378 events is almost constant for artificial impacts (before 1973), but it presents  
 379 strong variations for deep moonquakes (after 1973) possibly due to both a  
 380 lower signal to noise ratio and a less diffuse wavefield. However, the relative  
 381 gain of X and Y components can be reasonably well estimated for all the  
 382 stations. For stations S12 and S14, only artificial impacts are taken into ac-  
 383 count. The Y component is then corrected for this instrumental effect before  
 384 performing the rotation in radial and transverse components for each deep  
 385 moonquake event.

#### 386 4.3. Correction of relative frequency responses of the stations

387 The horizontal component records of seismometers from the Apollo 14  
 388 and Apollo 16 missions present frequency contents significantly different from  
 389 those of Apollo 12 and Apollo 15 missions. Figure 8a presents a logarithmic  
 390 average of the power spectral densities of all the deep moonquake signals  
 391 selected per seismic station. Apollo 14 seismic station presents an addition-

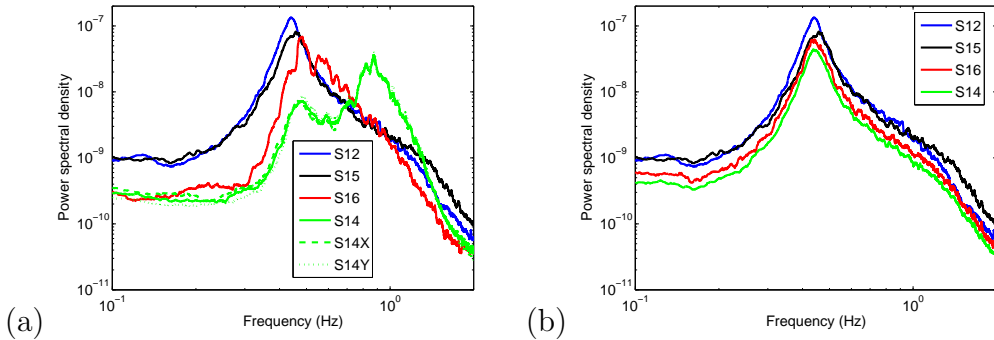


Figure 8: Logarithmic average of power spectral densities over all deep moonquake transverse records before (a) and after (b) correction of S14 and S16 transfer functions as a function of frequency for seismic stations S12 (in blue), S14 (in green), S15 (in black) and S16 (in red). On the left, curves for sensors X (dashed green) and Y (dotted green) of station S14 are also presented. All the curves have been smoothed by a moving average filter over 251 points in order to clarify the figures. Amplitude differences are due to differences of energy between the different deep moonquake records.

392 nal spectral peak at a frequency of 0.87 Hz, and Apollo 16 seismic station  
 393 presents lower energy at low frequency compared to Apollo 12 and 15 sta-  
 394 tions. These anomalous features observed on the two horizontal sensors are  
 395 not present on the vertical components of the records (not shown). It sug-  
 396 gests that this effect is mainly due to the response of the ground just below  
 397 the stations (site response). However, in order to be able to use the phase of  
 398 the records in stacks, these records must have a similar frequency content.  
 399 The spectral amplitudes of S14 and S16 transverse components have thus  
 400 been corrected by a spectral amplitude ratio computed between these sta-  
 401 tions and an average value between stations S12 and S15. The power spectral  
 402 densities obtained after correction are presented in Figure 8b. These correc-  
 403 tions of S14 and S16 records give a power spectral density similar to stations  
 404 S12 and S15.

#### 405 4.4. Data filtering

406 S waves usually have more energy at lower frequencies. Moreover, we  
 407 expect both the crustal scattering and the attenuation to be reduced at low  
 408 frequencies. Consequently, the Apollo data recorded in peaked mode were  
 409 converted into the long period mode by using theoretical responses of these  
 410 two acquisition modes, and filtered by an order 3 butterworth band pass filter  
 411 with corner frequencies at 0.3 Hz and 0.9 Hz. This operation allows us to

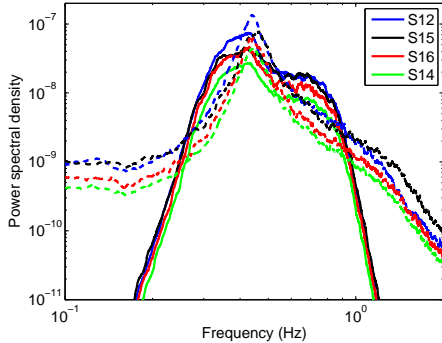


Figure 9: Logarithmic average of power spectral densities over all deep moonquake transverse records before (dotted lines) and after (plain lines) modes conversion and filtering as a function of frequency for seismic stations S12 (in blue), S14 (in green), S15 (in black) and S16 (in red). All the curves have been smoothed by a moving average filter over 251 points in order to clarify the figures.

412 enlarge and equalize the available frequency band. The frequency limits have  
 413 been chosen by trial and error in order to minimize the high frequency signal,  
 414 and to reduce as much as possible the lower cut off frequency. Below 0.3 Hz  
 415 and above 0.9 Hz, the noise dominates the signal in stacks of Apollo deep  
 416 moonquake data. Figure 9 presents power spectral densities of the signals  
 417 before and after the filtering process.

#### 418 4.5. About polarisation filtering

419 Weber et al. (2011) used polarisation filtering in order to detect body wave  
 420 arrivals reflected by deep Moon discontinuities. We evaluate the performance  
 421 of this filter for picking S waves and detecting reflections from deep Moon  
 422 discontinuities.

423 The polarisation filtering described in Weber et al. (2011) is a non linear  
 424 method allowing to enhance linearly polarized seismic arrivals. Assuming  $\frac{V_S}{V_P}$   
 425 ratio equal to 0.5 in the lunar regolith (Gagnepain-Beyneix et al., 2006), P  
 426 and S body waves are linearly polarized for incidence angles smaller than  
 427  $60^\circ = \sin^{-1}\left(\frac{V_S}{V_P}\right)$  Nuttli (1961). Therefore, this method can be applied to  
 428 most teleseismic P and SV wave arrivals on the Moon. However, assuming  
 429 that SH waves are present only on the transverse component, such filtering  
 430 is useless for these waves.

431 The radial ( $R$ ) and transverse ( $T$ ) components are computed from  $X$  and  $Y$   
 432 records by the following relation, assuming that  $X$  and  $Y$  sensors are aligned

433 respectively along East and North directions (the real orientations of the  
 434 sensors is given in Table 3):

$$\begin{bmatrix} R \\ T \end{bmatrix} = \begin{bmatrix} \sin \theta & \cos \theta \\ -\cos \theta & \sin \theta \end{bmatrix} \times \begin{bmatrix} X \\ Y \end{bmatrix} \quad (9)$$

435 where  $\theta$  is the azimuth of the event at the receiver. In the following we  
 436 will note the real (true) displacements with superscripts  $T$  and the measured  
 437 displacements without superscript, and assume that  $Y = Y^T$  and  $X = \gamma X^T$ .  
 438 The gain corrections for the horizontal components has been presented above,  
 439 and  $\gamma$  is equal to the X/Y ratio determined previously. If this correction is  
 440 not applied before the rotation of X and Y components, the relations between  
 441 measured radial and transverse components and the true ones is the following:

$$\begin{bmatrix} R \\ T \end{bmatrix} = \begin{bmatrix} \gamma \sin \theta & \cos \theta \\ -\gamma \cos \theta & \sin \theta \end{bmatrix} \times \begin{bmatrix} \sin \theta & -\cos \theta \\ \cos \theta & \sin \theta \end{bmatrix} \times \begin{bmatrix} R^T \\ T^T \end{bmatrix} \quad (10)$$

442 In particular, the radial component can be expressed as  $R = a_{11}(\gamma)R^T +$   
 443  $a_{12}(\gamma)T^T$  with  $a_{ij}(\gamma)$  being the terms of the matrix  $A$  corresponding to the  
 444 matrix product described above.

445 The polarisation filter (Weber et al., 2011) can be written as  $OZ_j = Z_jM_j$   
 446 and  $OR_j = Z_jM_j$  respectively along the vertical and radial components, with  
 447  $M_j = \sum_{i=-n}^n Z_{j+i}R_{j+i}$ , where  $j$  is the time step and  $n = 6$ . Now assuming  
 448 that SV body wave has a motion  $W_j^S$  and an incidence angle  $j_o$ , and that  $\epsilon_z$   
 449 and  $\epsilon_r$  are respectively the noise on the vertical and radial component, the  
 450 true vertical and radial components can be written as  $Z_j^T = W_j^S \sin(j_o) + \epsilon_z$   
 451 and  $R_j^T = W_j^S \cos(j_o) + \epsilon_r$ . Reporting these equations in (10), and assuming  
 452  $Z = Z^T$ , we obtain

$$Z_jR_j = (W_j^S \sin(j_o) + \epsilon_z) [a_{11}(\gamma)W_j^S \cos(j_o) + a_{11}(\gamma)\epsilon_r + a_{12}(\gamma)T^T] \quad (11)$$

453 Consequently, the non linear polarisation filter is subject to two different  
 454 noise sources. First, the term  $a_{12}(\gamma)T^T$  perturbs the radial component. Sec-  
 455 ond, the SV wave signal should be over the noise level along the vertical  
 456 component ( $W_j^S \sin(j_o) \gg \epsilon_z$ ) in order to ensure enhancement of the SV  
 457 wave signal. Our tests demonstrate that the first noise source due to wrong  
 458 rotation in the horizontal plane is generally negligible because  $\gamma$  is close to  
 459 one. Figure 10 presents the polarisation filtering performed on raw deep  
 460 moonquake stacks after rotation for event A01 and station S15. This figure

461 can be compared directly to figure S1 of Weber et al. (2011). SV wave signal  
 462 is clearly enhanced by the polarisation filtering both on OZ and OR because  
 463 the SV wave signal is clearly dominating noise on both vertical and radial  
 464 components. Such a clear enhancement of SV pulse by polarisation filtering  
 465 is not observed in Weber et al. (2011) study. This comparison suggests that  
 466 the stacks of individual deep moonquake signals coming from the same deep  
 467 moonquake cluster (A01 in this case) was performed differently between the  
 468 two studies.

469 Because the polarisation filtering is able to enhance the coherent SV wave  
 470 signal on both radial and vertical components, we can use this information  
 471 in order to refine the arrival time picks of SV waves and to infer the length  
 472 of the SV pulse. Figure 11 presents a focus on the polarisation filtering of  
 473 radial components around the SV arrival. The SV wave arrivals are clearly  
 474 enhanced by this process on both the raw and filtered records. More interest-  
 475 ingly, the SV pulse length can be estimated in the 5 to 10 seconds range, and  
 476 it looks to be varying more with event number than with station number.  
 477 This observation suggests that the pulse length reflects more the properties  
 478 of the signal coming from the source region than the variation of scattering  
 479 properties below the stations.

480 However, P and S waves reflected back from discontinuities at radius smaller  
 481 than 500 km inside the Moon have incidence angles smaller than  $2^\circ$ . Ther-  
 482 fore, the amplitude of the SV wave on the vertical component is predicted  
 483 to be at best 4% of the one on the radial component. Due to the high coda  
 484 energy and to the low signal to noise ratio of deep moonquake stacks, the SV  
 485 wave signal coming from deep reflectors inside the Moon will be smaller than  
 486 the noise on the vertical component ( $W_j^S \sin(j_o) \ll \epsilon_z$ ). The same argument  
 487 also holds for deep reflections arriving as P waves at the station. In this case,  
 488 the polarisation filtering will only enhance time intervals for which the noise  
 489 (or coda signal) is in phase on both components.

490 In conclusion, the polarisation filtering is useless for ScSH wave detection.  
 491 It gives good results for SV and P waves when the incidence angle is not  
 492 too small, and allows us to estimate the length of the S pulse in the 5-10  
 493 s range. However, it cannot be used for the detection of waves reflected by  
 494 deep discontinuities inside the Moon because in this case the noise dominates  
 495 the signal on one component, and both *OZ* and *OR* filtered signals present  
 496 enhancements for time intervals for which *Z* and *R* codas are in phase. For  
 497 all these reasons, we decided not to use this method for ScSH wave detection.

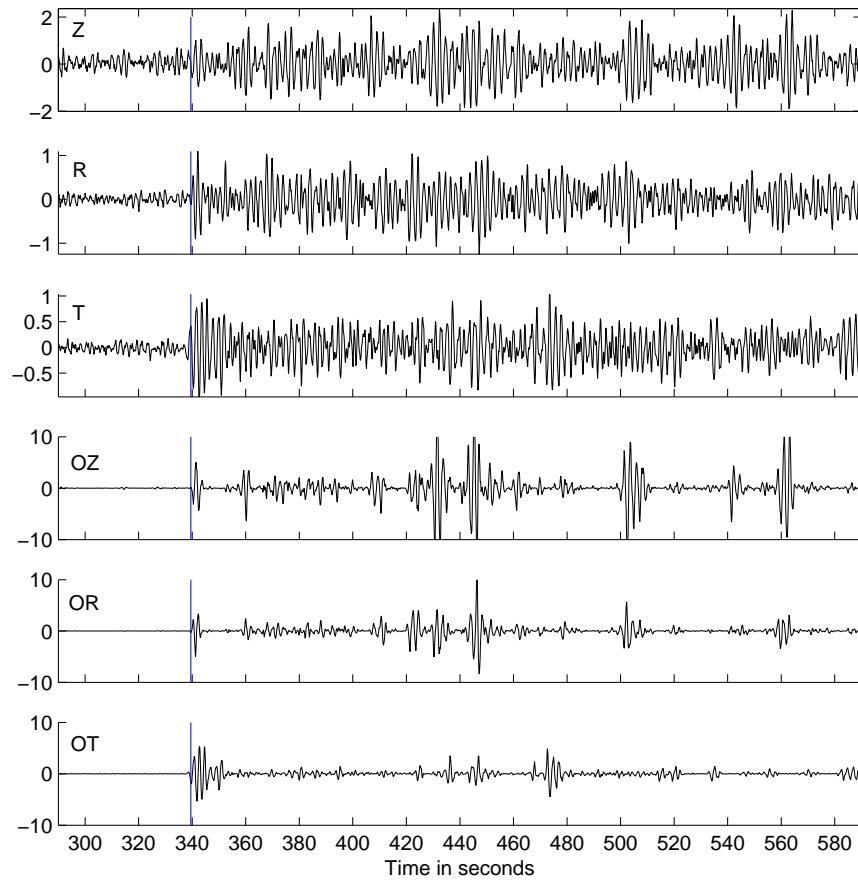


Figure 10: (top three traces): Raw deep moonquake stacks components (cluster A1) at Apollo station 15. (bottom three traces): Polarization filtered components of the same stack. S wave arrival time predicted by our best model (blue line) is presented.



Table 3: Azimuth (in degree) of X and Y sensors extracted from Apollo Scientific Experiments Data Handbook available at [http://nssdc.gsfc.nasa.gov/planetary/online\\_books.html](http://nssdc.gsfc.nasa.gov/planetary/online_books.html)

Station name	X azimuth (in deg.)	Y azimuth (in deg.)
S12	180	270
S14	0	90
S15	0	90
S16	334.5	64.5

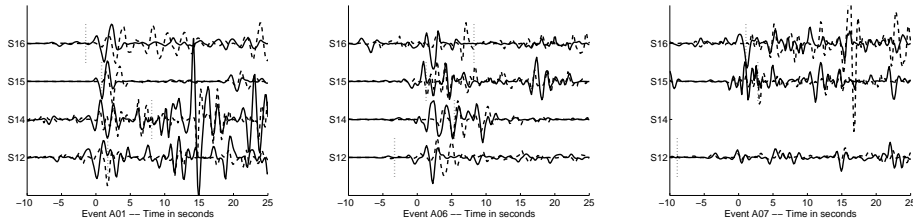


Figure 11: Polarisation filtering of radial components ( $OR_j$ ) aligned on the hand picked SV wave arrival times for raw records (dashed lines) and records after filtering (plain lines). From top to bottom, records of stations S12, S14, S15 and S16. From left to right, records for events A01, A06 and A07. The vertical component of station S14 for event A07 is not available in our data base, consequently the polarisation filtering cannot be performed. The vertical dotted lines indicate the S wave arrival time predicted by our best moon model.

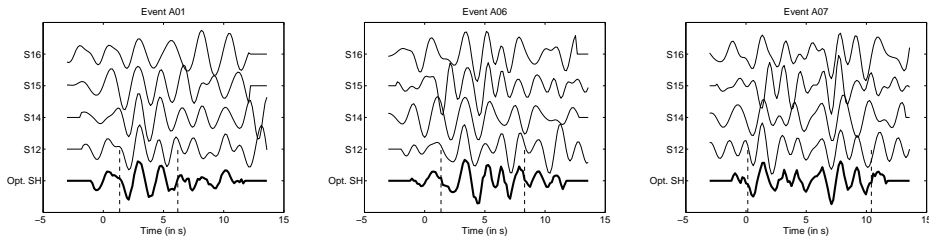


Figure 12: Results of the SH wave optimal waveform and delay times inversion. From bottom to top, optimal SH waveform (thick line) and filtered records of stations S12, S14, S15 and S16 after optimal alignment. From left to right, records for events A01, A06 and A07. Vertical dashed lines delimit the time interval with maximum coherent energy which is used below to define the optimal SH waveform.

#### 498 4.6. S wave alignment and differential travel time computations

499 The arrival times of S waves on the transverse components of deep moon-  
500 quake stacks are hand picked by visual inspection of vertical, radial and  
501 transverse components. During this process, the polarity of some records  
502 has been changed in order to ensure similar polarities of S waveforms for the  
503 different records of the same deep moonquake. The stacks of deep moonquake  
504 records strongly depend on the S wave arrival time. In order to obtain a very  
505 precise alignment of SH wave between the different stations, the records are  
506 inverted by a non-linear method searching for optimal SH waveform and  
507 relative delay times between the stations (Chevrot, 2002). Results of this  
508 waveform matching procedure are presented in figure 12. Interestingly, the  
509 best matching waveform presents significant energy on a length that is con-  
510 sistent with the SV pulse lengths obtained by polarisation filtering ( $\approx 5$  s for  
511 A01,  $\approx 7$  s for A06,  $\approx 10$  s for A07). The SH hand picks are corrected by  
512 delays deduced from this analysis.

513 The arrival times of S and ScS waves are computed inside the best radial mod-  
514 els for each core radius using the deep moonquake relocations obtained for  
515 these models. These computations are performed by a new implementation  
516 of the Tau-P algorithm (Buland and Chapman, 1983; Calvet and Chevrot,  
517 2005).

#### 518 4.7. Stacking process

519 All the waveforms are aligned on the S wave arrivals and normalized to  
520 maximum amplitude of the first one hundred seconds of the coda. Again,

521 events with less than four recording stations and events for which horizon-  
 522 tal location errors produce relative differential times between stations larger  
 523 than half the dominant period ( $\approx 1.25$  s) are excluded. Only high quality  
 524 events A01, A06 and A07 are kept. The stacks of the waveforms for each  
 525 event are performed by computing the differential times ScS-S for a given  
 526 moonquake depth  $D_i$  and a given core radius  $R_{core}$  using the corresponding  
 527 best radial model. After alignment and stack, the ScSH waveform energy  
 528 is computed in a 10 second window after the predicted arrival time on the  
 529 stacked trace. This process is repeated for all the best radial models ob-  
 530 tained previously corresponding to core radii between 250 km and 490 km  
 531 with a 5 km step, and for event depth in the  $\pm 400$  km range around the  
 532 epicenter location with a 2 km step. Such a process allows us to compute,  
 533 for each event  $i$ ,  $NRJ_i^{ScS}(R_{core}, D_i)$  the energy of stacked ScS waveforms  
 534 depending on core radius  $R_{core}$  and event depth  $D_i$ . The semblance of the  
 535 stacked records is also defined as the ratio between the stacked ScS wave-  
 536 form energy and the average energy of the records used to perform the stack  
 537 (Neidell and Taner, 1971). This parameter is varying between zero (complete  
 538 destructive interference) and one (fully constructive interference), providing  
 539 a measure of stack efficiency normalized to the energy of the records. As for  
 540 the energy, the semblance depends on core radius  $R_{core}$  and event depth  $D_i$ :  
 541  $SEMB_i^{ScS}(R_{core}, D_i)$

542 In order to include additional a priori information on the events depth,  
 543 stacked energies and semblances are multiplied by a gaussian function of the  
 544 form  $G_i(D_i) = \exp(-\frac{(D_i - D_i^0)^2}{\sigma_i^2})$  with  $D_i^0$  the a priori event depth and  $\Delta D_i^0$  its  
 545 error. The standard deviation of the gaussian is defined by  $\sigma_i = 10\Delta D_i^0$ , in  
 546 order to allow large variations around the a priori event depth. A priori deep  
 547 moonquake locations and related errors on the parameters are extracted from  
 548 the study by Gagnepain-Beyneix et al. (2006). This weight function  $G_i(D_i)$   
 549 is only a smooth way to impose event depth in the  $\pm 5\Delta D_i^0$  range around  
 550 theoretical value.

551 Figure 13 shows the ScSH stack energies obtained for the three events A01,  
 552 A06 and A07. On these plots, a correlation between core radius and event  
 553 depth is clearly seen. However, the ScSH energy presents a peak in the  
 554 380-400 km core radius range for the three events.

555 Once these energies are computed, their maximum value for each core ra-  
 556 dius are defined by  $NRJmax_i^{ScS}(R_{core}) = \max_{D_i} [NRJ_i^{ScS}(R_{core}, D_i)]$ . These  
 557 functions are plotted in figure 14(a-c) for the three events selected. They

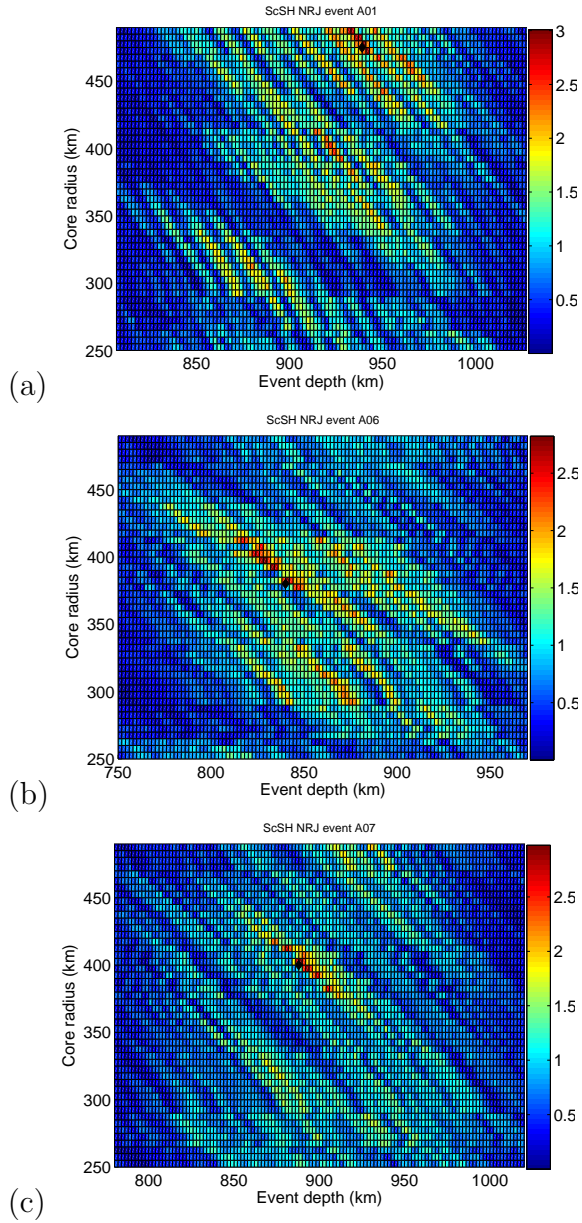


Figure 13: Stacked energies  $NRJ_i^{ScS}(R_{core}, D_i)$  in color, as a function of core radius (in km) and event depth (in km), for events A01 (a), A06 (b) and A07 (c). The energies are multiplied by a gaussian function  $G_i(D_i)$  centered around a priori depth  $D_i^0$ . Color goes from blue (low energy) to red (high energy), and the maximum value is indicated by a black diamond.

558 present a global or local maximum in the 380-400 km core radius range.  
559 However, the statistical test performed below demonstrate that, when taken  
560 separately, the maxima of these events are statistically significant only for  
561 events A06 and A07.  
562 To investigate the statistical significance of the results, we consider the av-  
563 erage of maximum ScS stack energies of individual events:

$$NRJsum(R_{core}) = \frac{1}{N_{ev}} \sum_i^{N_{ev}} NRJmax_i^{ScS}(R_{core}) \quad (12)$$

564 with  $N_{ev}$  the number of events. However, even if the records are scaled before  
565 the stacking process,  $NRJmax_i^{ScS}(R_{core})$  functions present different ampli-  
566 tudes for the different events. In our case,  $NRJsum(R_{core})$  is dominated by  
567 events A01 and A06. In order to give an equal weight to all the events, these  
568 functions are scaled to their standard deviation and their mean is substracted  
569 before summation in order to produce energy plots including all the events  
570 with a similar contribution. The final result is a scaled energy depending  
571 only on core radius which is defined for ScS waveform stacks by:

$$\overline{NRJ}sum(R_{core}) = \frac{1}{N_{ev}} \sum_{i=1}^{N_{ev}} \frac{(NRJmax_i^{ScS}(R_{core}) - \langle NRJmax_i^{ScS}(R_{core}) \rangle)}{std(NRJmax_i^{ScS}(R_{core}))} \quad (13)$$

572 with  $\langle \rangle$  and  $std()$  respectively the average and standard deviation operators.  
573 The same operations are performed for the semblance by computing for each  
574 event the maximum semblance at different core radius ( $SEMBmax_i^{ScS}(R_{core})$ )  
575 and the average of these curves over all the events ( $SEMBsum(R_{core})$ ). The  
576 scaled version of semblance curve does not have to be computed because  
577 the semblance measure is already normalized to the energy of the records.  
578 Functions  $NRJsum(R_{core})$ ,  $\overline{NRJ}sum(R_{core})$  and  $SEMBsum(R_{core})$  are pre-  
579 sented in panels (d), (e) and (f) of figure 14. This figure demonstrates that  
580 when the three events are taken together the energy maximas at 380 and  
581 395 km core radius are statistically significant (at three standard deviations  
582 level).

583 In order to test the dependence of the results on the filtering process, the  
584 whole process (including S wave alignment) is repeated on the data before ac-  
585 quisition mode conversion and bandpass filtering. The results are presented  
586 in panels (g), (h) and (i) of figure 14. The peaks of ScSH wave energy around

587 380 and 395 km core radius are also present but less statistically significant.  
588 The consistency of the results between the two different frequency ranges  
589 strongly argue in favour of a ScSH detection. Moreover, the lower ScSH en-  
590 ergy at high frequencies (in peaked mode) than at low frequencies (in long  
591 period bandpass mode) justifies the search for this body wave at frequencies  
592 as low as possible.

593 Because the ScSH wave stacks may be slightly shifted inside the ten seconds  
594 time window, the core radius obtained may be also shifted. For example,  
595 if the energy of ScSH wave stack inside the window is significant only 2 or  
596 3 s after the beginning of the window, S-ScS travel time is under-estimated  
597 and core radius over-estimated. In order to remove this effect, the records  
598 obtained after filtering have been deconvolved from the optimal source time  
599 functions presented on figure 12. After deconvolution, SH energy is focused  
600 on a 2 s window. The stacking process is reproduced by computing energy on  
601 a 2 s window centered on the ScS arrival. The results are presented in figure  
602 15, for the three different moonquakes. Clear maximas of ScSH energy are  
603 obtained for events A06 and A07, but at slightly smaller core radius (370-390  
604 km), which suggests that the over-estimation of the core radius due to the  
605 10 s window may be real. However, the small size of stacking window has  
606 the drawback to focus the stack energy in a very narrow core radius range.  
607 Due to quake mislocations and also possibly to lateral heterogeneities at the  
608 base of the lunar mantle, the real ScS-S differential travel times vary from  
609 one event to the other and different core radius are obtained for the different  
610 events. As a consequence, the three curves do not interfere constructively  
611 when summed together.

612 The test presented above and the increasing difficulty to explain geodesic  
613 observations with increasing core radius above 380 km, favour a core radius  
614 value at the lowest range of the broad energy peak observed on figure 14.  
615 Optimal core radius estimate is 380 km, with a 30 km error bar estimated  
616 from the range of core radius for which the energy is above the two standard  
617 deviation level.

618 A similar exercise is also done for the radial components of the records  
619 in order to detect ScSV waves. The results obtained on filtered data are  
620 presented on figure 16. As expected, ScSV wave is not detected inside the  
621 S coda because its amplitude is smaller than ScSH one. This exercise also  
622 demonstrates that the bootstrap method described below is pertinent for the  
623 validation of ScSH detections.

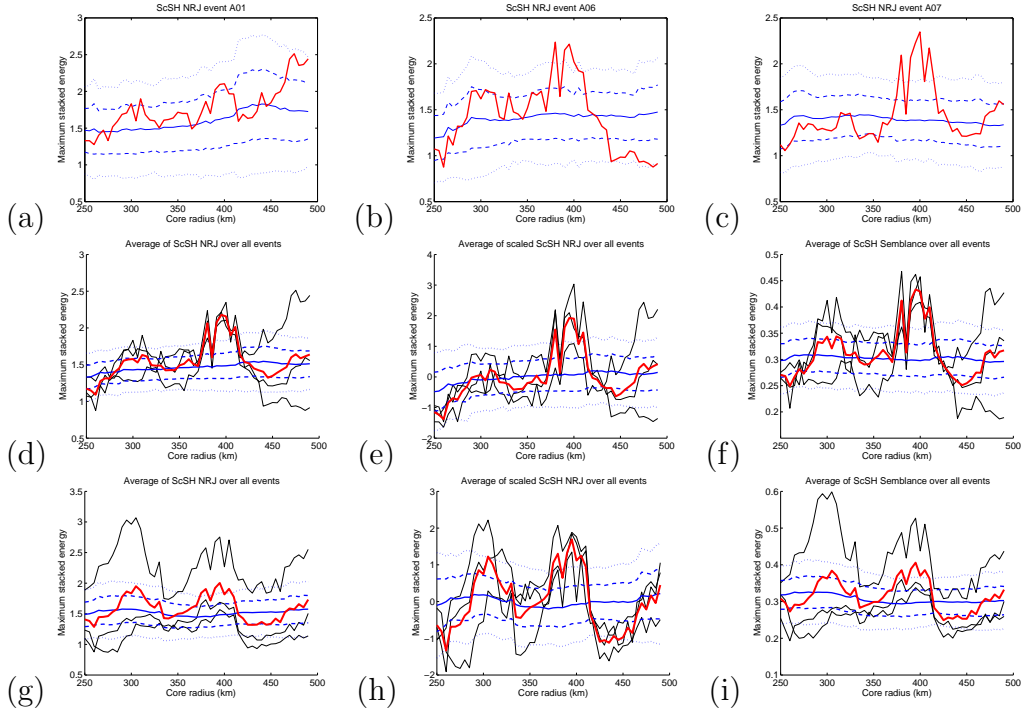


Figure 14: Plots of stacked maximum energies  $NRJmax_i(R_{core})$  for events A01 (a), A06 (b), A07 (c), and the average of these energies  $NRJsum(R_{core})$  (d), the scaled average of these energies  $\overline{NRJsum}(R_{core})$  (e) (red curves), and the average semblance  $SEMBsum(R_{core})$  (f) (red curve). Panels (g), (h) and (i) are identical respectively to panels (d), (e) and (f), but for data before acquisition mode conversion and bandpass filtering. The average value (blue plain line), the one standard deviation around this value (blue dashed lines) and the two standard deviation value (blue dot-dashed line) obtained for the bootstrap ensemble are shown on each plot. On panels (d), (e), (f), (g), (h) and (i) curves for individual events (thin black lines) are also presented.

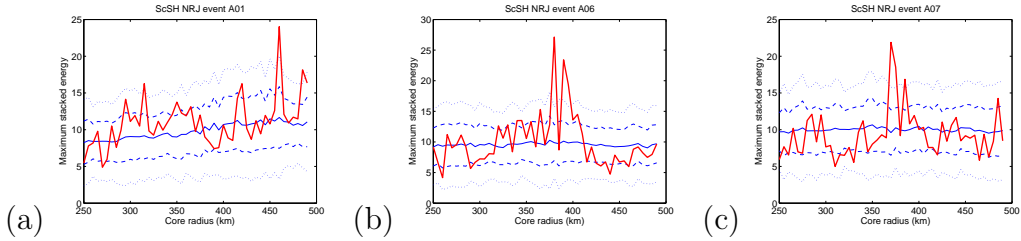


Figure 15: Plots of stacked maximum energies  $NRJmax_i(R_{core})$  after deconvolution of optimal SH waveforms for events A01 (a), A06 (b), A07 (c). The average value (blue plain line), the one standard deviation around this value (blue dashed lines) and the two standard deviation value (blue dot-dashed line) obtained for the bootstrap ensemble are shown on each plot.

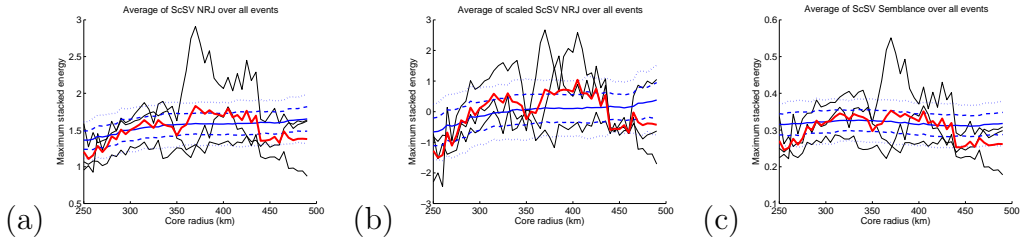


Figure 16: Plots of  $NRJsum(R_{core})$  (a),  $\overline{NRJsum}(R_{core})$  (b) and  $SEMBsum(R_{core})$  (c) (red curves) for stacks of the radial components of the records. The average value (blue plain line), the one standard deviation around this value (blue dashed lines) and the two standard deviation value (blue dot-dashed line) obtained for the bootstrap ensemble are shown. Curves obtained for individual events (thin black lines) are also presented.



624 *4.8. Validation of the results with bootstrap*

625 We applied a bootstrap method to test the statistical significance of our  
626 results (Efron and Tibshirani, 1993). The SH arrival picks are perturbed  
627 randomly in a  $\pm 30$ s range. We repeat the stacking process for each new  
628 data set. We then compute the mean, maximum and standard deviation  
629 over 150 random realizations of the resulting stacks of energy. This method  
630 gives an estimate of the background noise corresponding to random waveform  
631 alignment. A peak can be considered significant if it is above two standard  
632 deviations of the bootstrap ensemble.

633 As described previously, the two standard deviation level is passed in the  
634 380-400 km core radius range for filtered data using a 10s window (Figure  
635 14), and in the 370-390 km core radius range after deconvolution of optimal  
636 SH waveforms for events A06 and A07. The statistical validation is obtained  
637 for ScSH detection and not for ScSV detection. Moreover, an error estimate  
638 of  $\pm 40$  km is provided. This error will be evaluated more precisely below.

639 *4.9. Stacked waveforms comparison*

640 Figure 17 presents record sections of transverse components aligned on  
641 predicted ScSH arrival for a 380 km core radius. After alignment on ScSH,  
642 the waveforms are stacked in order to produce a ScSH stacked waveform for  
643 each event. Similar processing is also done for the SH wave. The comparison  
644 of these stacked waveforms is shown in figure 18. In this figure, the SH  
645 and ScSH waveforms have been cross-correlated on a 10 s window, and are  
646 presented for the best correlation within a  $\pm 2$  s time shift of ScSH stack.  
647 This shift correspond to the value of  $\Delta t_d$  due to the error on the (longitude,  
648 latitude) coordinates of the quake, and it should be below 2 s for the events  
649 processed in this study. A good correlation between ScSH and SH stacks is  
650 obtained for events A06 and A07, but it is low for event A01. This waveform  
651 similarity, already enhanced by the success of stacking after deconvolution of  
652 SH optimal waveform, gives further support for a ScSH detection.

653 **5. Discussion**

654 *5.1. Error estimates*

655 Figure 14 provides a formal error estimate on the core radius which takes  
656 into account the uncertainty in the stacking process, and errors on the depth  
657 of the events. However, the error on the seismic model must also be taken

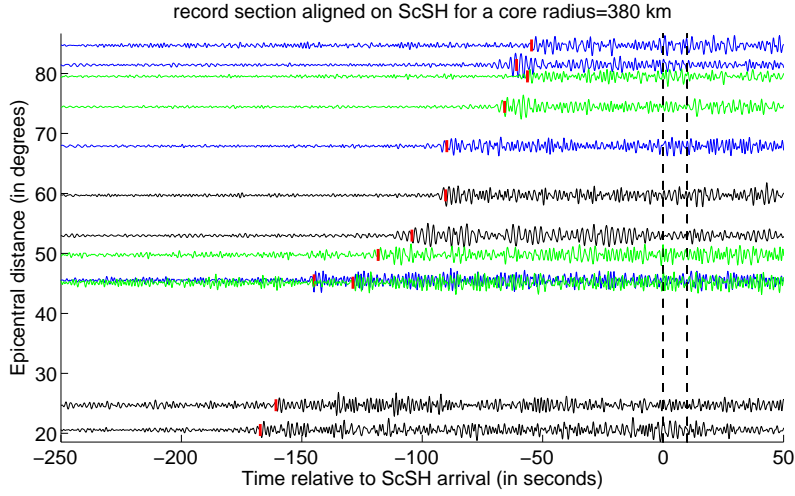


Figure 17: Record sections of transverse components plotted as a function of epicentral distance (in degrees) and time relative to predicted ScSH arrival time for a 365 km core radius (in seconds). Red marker indicate the SH wave arrival time pick. Vertical dashed lines indicate the 10 second window used to stack ScSH waveforms. Different colors are used for the different quakes: A01 in black, A06 in blue and A07 in green.

658 into account in order to estimate its effect on the core radius. From the set  
659 of models generated by the NA algorithm at 380 km radius, we compute the  
660 maximum and minimum values of seismic velocities and densities at each  
661 depth inside the ensemble of models within the half width of the probability  
662 peak. These values define the error bars on the best radial model. They  
663 are plotted on figure 19a. These error bars are almost constant inside the  
664 mantle for density and P-wave velocity with a relative error of respectively  
665 0.2% and 3.3%. However, the error on S-wave velocity presents a minimum in  
666 the mid-mantle (3%) and a maximum (11%) at the base of the mantle. The  
667 strong increase in S-wave velocity errors at the base of the mantle translates  
668 to a significant error on the absolute value of core radius. Considering a  
669 vertically incident ScS wave from a deep moonquake at a depth of 900 km,  
670 the integrated error on the S-wave velocity profile below the event produces  
671 an error on the ScS travel time of about 9% on the two-way travel time from  
672 the event to the core, or about 19 s. This travel time error can be translated  
673 directly into an error on the core radius of approximately 33 km. This rough  
674 estimate is probably an upper estimate because the vertical incidence of ScS  
675 rays has the highest sensitivity to core radius. However, it highlights the

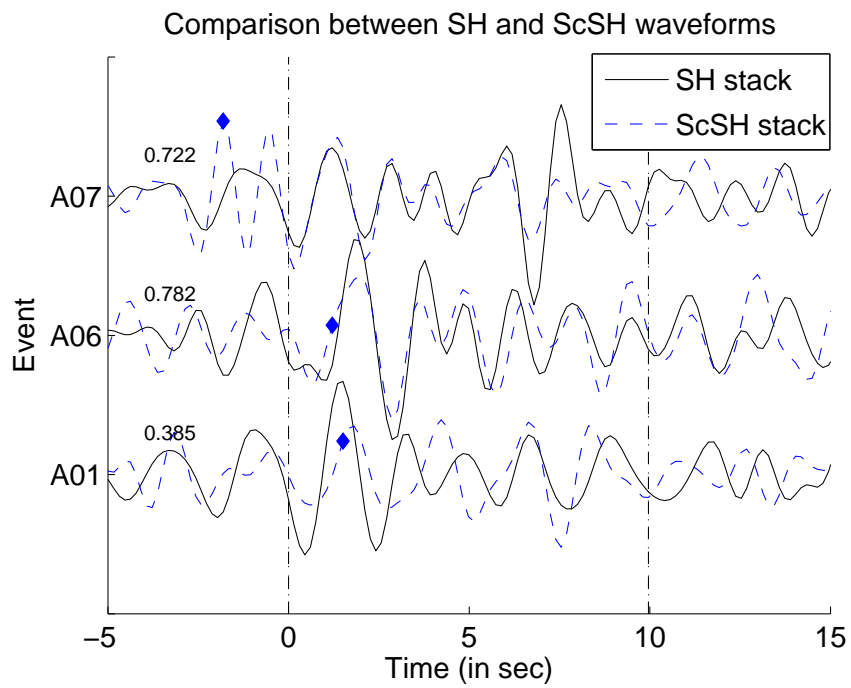


Figure 18: Comparison between SH (black plain line) and ScSH (blue dashed line) stacks as a function of time and event number. The ScS stacks are aligned for best correlation in the  $\pm 2$  seconds range. Blue diamonds indicate the start of ScS stack window before alignment. Events numbers are 1 for A01, 2 for A06 and 3 for A07. Correlation coefficient over the 10 seconds window is indicated along the stack before the stack window.

676 difficulty to obtain an absolute value of core radius without S-wave arrival  
677 time measurements at large epicentral distances. Taking into account the  
678 true ray geometries, and the bootstrap analysis of ScSH wave detection, the  
679 error bar on the core radius is about 40 km.

680 The error on the average core density for a 380 km core radius is about 0.3  
681  $\text{kg}/\text{cm}^3$ . By looking at figure 4c, varying the core radius in a range of  $\pm 40$   
682 km around its best estimate gives approximately two times larger average  
683 core density variation than the error bar estimate at 380 km core radius.  
684 Moreover, because the core density is inferred from mass and moment of  
685 inertia, and due to the low value of the core moment of inertia (of the same  
686 order as the error bar on the moment of inertia of the whole planet), small  
687 variations of crustal thickness and density may generate large variations of  
688 core density. The average crustal thickness is not inverted here, but the  
689 error on this parameter requires to increase our estimate of the error on the  
690 core density. Consequently, a conservative estimate of average core density  
691 is  $5.2 \pm 1.0 \text{ kg}/\text{cm}^3$ .

## 692 *5.2. Comparison with previous results*

693 Our estimates of core radius at  $380 \pm 40$  km and average core density at  
694  $5.2 \pm 1.0 \text{ kg}/\text{cm}^3$  are respectively at the upper and lower limits of previous  
695 estimates from both lunar laser ranging observations (Williams et al., 2001)  
696 and induced magnetic moment of the Moon (Hood et al., 1999). This seis-  
697 mic estimate of core radius is significantly larger than the 330 km proposed  
698 by Weber et al. (2011), which in some way indicates a large sensitivity to  
699 uncertainties in the seismic model at the base of the mantle and to error  
700 propagation. However their large error bars of these core radius estimates  
701 cover the domain of previously inferred values. Moreover, the detection of  
702 ScSH waves and not ScSV waves supports a liquid core beneath the core  
703 mantle boundary, as already suggested by the dissipation of lunar rotation  
704 (Williams et al., 2001). The average core density is relatively low and sug-  
705 gests either a high level of light elements in a completely fluid core, or a large  
706 core temperature. For example, if the average core density is explained by  
707 the presence of sulfur alone, more than 10% are required for the nominal  
708 value (Sanloup et al., 2000; Balog et al., 2003). But, when the error bar is  
709 taken into account the percent of sulfur content can vary from almost zero to  
710 large values. However, because an inner core is expected for thermodynam-  
711 ical reasons (Wieczorek et al., 2006) and its size is not constrained by this

712 study, the interpretation of the average core density into core composition is  
713 strongly limited.

## 714 6. Description of the best model

715 This section gives seismic event location parameters, station corrections,  
716 and the reference model. The reference model is denominated VPREMOON  
717 for Very Preliminary REference MOON model. The parameter values, and  
718 related error bars at fixed core radius, for this model are:  $\rho_c = 2.762 \pm 0.0048$ ,  
719  $a = -8.0783 \pm 0.790$ ,  $b = 4.728376 \pm 0.245$ ,  $A = 1.816595 \pm 0.313$ ,  $B =$   
720  $-0.000054 \pm 0.000251 km^{-1}$  and  $R_{core} = 380 km$ . In this model, calcu-  
721 lated values of geodesic observations are  $k_2^{calc} = 0.0223$ ,  $h_2^{calc} = 0.0394$ ,  
722  $IR^{calc} = 0.3932$  and  $l_2^{calc} = 0.0106$  (this last parameter is not inverted here).  
723 The values obtained at best fit are  $\chi_{seismo}^2 = 1.4814$  and  $\chi_{geod}^2 = 0.0575$ . For  
724 comparison, our starting model derived from Gagnepain-Beyneix et al. (2006)  
725 model gives  $k_2^{calc} = 0.0231$ ,  $h_2^{calc} = 0.0408$ ,  $IR^{calc} = 0.3931$ ,  $l_2^{calc} = 0.0110$ ,  
726  $\chi_{seismo}^2 = 6.232$  and  $\chi_{geod}^2 = 0.301$ .

727 Table 4 provides the relocations of the events used in this study inside the  
728 VPREMOON model. These locations are close to the locations published by  
729 Gagnepain-Beyneix et al. (2006) because the seismic model is very similar in  
730 most of the mantle. The errors on these locations are underestimated, be-  
731 cause the uncertainty on the velocity model is not formally taken into account  
732 in their computation. Table 5 gives station corrections. These corrections  
733 are small and their relative error is large. Table 6 and figure 19 present the  
734 VPREMOON model. The model is separated in a seismic model in which  
735 the crustal thickness (28 km) is compatible with near side crustal structure  
736 below the Apollo network, and a geodesic model in which the Moho depth  
737 is corrected to its average value over the whole planet (40 km). P wave ve-  
738 locity inside the core is not constrained by our study. Assuming that the  
739 average core density is similar to the density of the liquid core, high pres-  
740 sure experiments suggest a P wave velocity close to 4.3 km/s at these pres-  
741 sure/temperature conditions (Sanloup et al., 2004). However, this value is  
742 not used in our model because the core internal structure is not constrained.  
743 P and S wave attenuations are taken from studies by Nakamura and Koyama  
744 (1982); Nakamura et al. (1982), and arbitrarily fixed in the deep mantle.

Table 4: Location parameters of the event used in the study inside the VPREM00N model.

Event name	lat. ( $\theta$ ) (in $^\circ$ )	long. ( $\phi$ ) (in $^\circ$ )	depth ( $z$ ) (in km)	$\sigma_\theta$ (in $^\circ$ )	$\sigma_\phi$ (in $^\circ$ )	$\sigma_z$ (in km)	origin date	origin time (in s)	$\sigma_{t_o}$ (in s)
12LM	-3.94	-21.20	0.0	0.00	0.00	0.0	6911202217	17.70	0.00
13S4	-2.75	-27.86	0.0	0.00	0.00	0.0	7004150209	41.00	0.00
14S4	-8.09	-26.02	0.0	0.00	0.00	0.0	7102040740	55.40	0.00
14LM	-3.42	-19.67	0.0	0.00	0.00	0.0	7102070045	25.70	0.00
15S4	-1.51	-11.81	0.0	0.00	0.00	0.0	7107292058	42.90	0.00
15LM	26.36	0.25	0.0	0.00	0.00	0.0	7108030303	37.00	0.00
16S4	1.30	-23.80	0.0	0.00	0.00	0.0	7204192102	4.00	0.00
17S4	-4.21	-12.31	0.0	0.00	0.00	0.0	7212102032	42.30	0.00
M1	73.52	2.79	0.0	0.64	2.77	0.0	7201040631	19.80	2.48
M2	1.55	-16.91	0.0	0.19	0.19	0.0	7205130846	39.04	0.56
M3	33.02	137.22	0.0	0.93	1.02	0.0	7207172150	56.66	1.29
M4	23.92	10.08	0.0	0.27	0.52	0.0	7207311808	15.23	1.68
M5	15.69	22.44	0.0	1.35	1.21	0.0	7208292258	33.50	2.85
M6	28.85	40.68	0.0	2.51	1.12	0.0	7309262046	16.32	2.88
M7	-24.60	-24.87	0.0	1.00	1.94	0.0	7312241003	19.38	2.93
M8	7.45	-33.32	0.0	0.65	0.90	0.0	7404191830	3.11	2.75
M9	20.23	6.46	0.0	0.41	0.63	0.0	7407171205	2.54	1.57
M10	-7.28	19.78	0.0	0.85	0.72	0.0	7411211315	40.51	2.45
M11	1.68	-8.15	0.0	0.87	0.39	0.0	7412150907	15.15	1.74
M12	-51.80	4.16	0.0	1.22	2.37	0.0	7503052149	22.25	2.92
M13	2.43	43.31	0.0	0.52	0.97	0.0	7504121812	38.22	2.92
M14	-37.16	-121.04	0.0	1.45	1.20	0.0	7505040959	28.51	2.34
M15	-39.24	62.77	0.0	1.79	1.46	0.0	7601130711	22.96	2.63
M16	-16.62	-9.87	0.0	0.96	0.68	0.0	7605280601	56.29	2.44
M17	23.69	-73.88	0.0	1.02	0.99	0.0	7611142313	6.60	2.38
M18	-20.39	-64.47	0.0	0.72	0.94	0.0	7704172332	6.87	2.44
M19	-13.06	-74.91	0.0	5.66	1.23	0.0	7706282222	31.15	2.86
SH1	12.78	50.78	15.9	1.42	2.69	68.6	7209171435	2.96	7.31
SH2	47.79	38.06	8.8	3.14	3.32	37.5	7212062308	33.52	8.23
SH3	-84.71	-137.13	71.3	0.85	1.48	38.6	7303130756	23.63	4.35
SH4	22.35	82.93	0.0	1.66	2.34	7.6	7407110046	19.16	6.53
SH5	26.32	-92.28	0.0	1.58	2.40	6.3	7501030141	56.19	5.10
SH6	65.81	58.96	20.3	1.02	1.13	13.3	7501120313	48.28	4.58
SH7	-16.93	-25.84	127.6	1.62	1.95	85.1	7502132203	50.43	6.68
SH8	44.15	33.94	168.1	2.31	1.84	94.4	7601041118	55.38	6.72
SH9	52.30	-25.83	136.3	0.77	1.08	37.3	7603061012	23.38	2.77
SH10	-18.71	-12.92	79.3	1.13	1.21	80.7	7603081442	10.63	5.28
A01	-17.31	-38.21	918.5	0.58	0.87	8.0	7309300410	58.29	1.40
A06	49.68	54.65	861.2	0.76	0.75	8.1	7607021052	23.70	1.16
A07	23.98	53.64	901.0	0.64	0.62	8.9	7607020311	22.88	1.18
A08	-27.99	-28.03	939.9	1.61	1.34	18.4	7705161052	28.80	3.00
A09	-37.71	-30.71	974.5	2.21	3.30	33.8	7704161958	3.76	4.89
A11	9.29	17.47	1200.4	0.68	0.76	10.3	7706180501	15.12	2.03
A14	-28.65	-33.80	880.6	1.22	1.32	15.8	7305281853	12.49	3.13
A16	6.83	5.07	1104.2	0.63	0.91	13.4	7210081524	35.05	2.04
A17	23.09	-18.00	861.1	1.20	1.32	13.3	7211070852	7.86	2.14
A18	18.56	34.66	882.1	1.39	0.92	18.6	7301052250	29.71	2.17
A20	21.72	-40.88	1055.3	0.63	1.83	10.5	7205151718	6.50	2.58
A24	-36.76	-38.81	980.1	1.79	1.68	26.2	7706121817	37.99	3.62
A25	34.33	59.23	899.3	1.52	1.35	19.4	7706092015	6.64	2.32
A26	12.14	10.13	1135.0	0.88	1.03	16.7	7706201450	48.48	3.08
A27	22.48	18.47	1058.7	1.29	1.53	11.0	7705160001	51.18	1.83
A30	11.81	-34.21	921.4	1.00	1.09	16.5	7205170042	45.35	2.37
A33	6.91	117.72	888.1	1.03	1.15	21.5	7210111935	44.93	2.37
A34	7.04	-9.29	931.4	0.65	0.82	18.3	7206141834	26.91	2.89
A40	-1.60	-10.93	885.4	0.88	0.62	17.5	7306272348	35.15	3.05
A41	13.88	-26.64	951.8	2.43	3.31	48.1	7206081616	24.56	7.43
A42	22.69	-53.38	1004.6	1.37	1.32	17.2	7305030152	34.84	2.44
A44	51.51	56.86	956.8	4.06	2.42	14.6	7405190309	3.63	3.71
A50	9.41	-51.45	835.5	1.23	1.63	21.5	7304300105	25.53	4.69
A51	8.85	15.75	887.1	0.55	0.83	18.4	7402180835	27.18	3.41
A84	-10.03	-31.76	862.2	1.97	2.43	17.3	7607221946	28.41	4.56
A85	27.90	59.16	801.7	1.38	2.87	20.2	7707191037	50.84	8.21
A97	-3.39	18.66	999.9	1.74	2.06	18.9	7705190608	21.00	3.51

Table 5: P and S wave station corrections and associated error bars.

Station name	P cor. (in s)	P cor. error (in s)	S cor. (in s)	S cor. error (in s)
S12	-1.034	0.250	-0.229	0.462
S14	1.162	0.230	-0.584	0.413
S15	-0.298	0.279	-0.950	0.468
S16	0.171	0.758	1.763	1.344

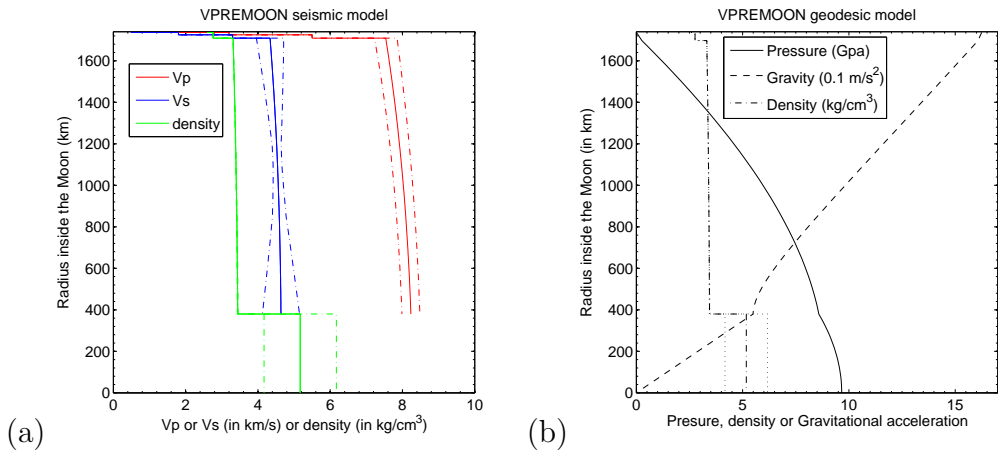


Figure 19: VPREMOON seismicological (a) and geodesic models (b). On the left (a), P and S wave velocities (in km/s) and density (in  $kg/cm^3$ ) are plotted as a function of radius (in km) for the seismicological model. The error bars are indicated for each parameters by dot-dashed lines. On the right (b), Pressure (in GPa), gravity (in  $0.1m/s^2$ ) and density (in  $kg/cm^3$ ) are plotted as a function of radius (in km) for the geodesic model.

Table 6: VPREMOON model: on the left the seismic model and on the right the geodesic model in which Moho depth as been corrected to 40 km. Attenuation parameters are extracted from previous studies (Nakamura and Koyama, 1982; Nakamura et al., 1982) and arbitrarily fixed in the deep mantle. Seismic velocities and attenuation parameters inside the core are arbitrarily fixed by the authors.

radius (in km)	$V_P$ (in km/s)	$V_S$ (in km/s)	density (in $kg/cm^3$ )	$Q_P$	$Q_S$	radius (in km)	density (in $kg/cm^3$ )	gravity ( $m/s^2$ )	pressure (in GPa)
1737.1	1.00	0.50	2.600	6750.0	6750.0	1737.1	2.600	1.6248	0.0000
1736.1	1.00	0.50	2.600	6750.0	6750.0	1736.1	2.600	1.6245	0.0056
1736.1	3.20	1.80	2.762	6750.0	6750.0	1736.1	2.762	1.6245	0.0056
1725.1	3.20	1.80	2.762	6750.0	6750.0	1725.1	2.762	1.6196	0.0781
1725.1	5.50	3.30	2.762	6750.0	6750.0	1725.1	2.762	1.6196	0.0781
1709.1	5.50	3.30	2.762	6750.0	6750.0	1709.1	2.762	1.6127	0.1825
1709.1	7.54	4.34	3.312	6750.0	6750.0	1697.1	2.762	1.6076	0.2599
1697.1	7.55	4.34	3.314	6750.0	6750.0	1697.1	3.314	1.6076	0.2599
1671.7	7.57	4.35	3.318	9000.0	4000.0	1671.7	3.318	1.5851	0.5086
1647.1	7.59	4.36	3.322	9000.0	4000.0	1647.1	3.322	1.5632	0.7470
1627.1	7.61	4.37	3.325	9000.0	4000.0	1627.1	3.325	1.5454	0.9389
1607.1	7.63	4.38	3.329	9000.0	4000.0	1607.1	3.329	1.5276	1.1290
1587.1	7.64	4.39	3.332	9000.0	4000.0	1587.1	3.332	1.5098	1.3174
1567.1	7.66	4.40	3.335	9000.0	4000.0	1567.1	3.335	1.4920	1.5040
1547.1	7.68	4.40	3.338	9000.0	4000.0	1547.1	3.338	1.4741	1.6888
1527.1	7.69	4.41	3.341	9000.0	4000.0	1527.1	3.341	1.4562	1.8718
1502.0	7.71	4.42	3.344	9000.0	4000.0	1502.0	3.344	1.4338	2.0988
1487.1	7.72	4.43	3.346	9000.0	4000.0	1487.1	3.346	1.4204	2.2321
1461.7	7.74	4.44	3.350	3375.0	1500.0	1461.7	3.350	1.3976	2.4570
1447.1	7.75	4.44	3.352	3375.0	1500.0	1447.1	3.352	1.3845	2.5848
1427.1	7.77	4.45	3.355	3375.0	1500.0	1427.1	3.355	1.3666	2.7583
1407.1	7.78	4.45	3.357	3375.0	1500.0	1407.1	3.357	1.3486	2.9297
1387.1	7.80	4.46	3.360	3375.0	1500.0	1387.1	3.360	1.3306	3.0992
1367.1	7.81	4.47	3.363	3375.0	1500.0	1367.1	3.363	1.3126	3.2666
1347.1	7.82	4.47	3.365	3375.0	1500.0	1347.1	3.365	1.2946	3.4320
1327.1	7.84	4.48	3.368	3375.0	1500.0	1327.1	3.368	1.2766	3.5954
1307.1	7.85	4.49	3.370	3375.0	1500.0	1307.1	3.370	1.2586	3.7566
1287.1	7.86	4.49	3.373	3375.0	1500.0	1287.1	3.373	1.2405	3.9157
1267.1	7.88	4.50	3.375	3375.0	1500.0	1267.1	3.375	1.2225	4.0728
1252.0	7.88	4.50	3.377	3375.0	1500.0	1252.0	3.377	1.2089	4.1899
1231.7	7.90	4.51	3.379	1125.0	500.0	1231.7	3.379	1.1906	4.3454
1207.1	7.91	4.51	3.382	1125.0	500.0	1207.1	3.382	1.1685	4.5308
1187.1	7.92	4.52	3.384	1125.0	500.0	1187.1	3.384	1.1505	4.6791
1167.1	7.94	4.53	3.386	1125.0	500.0	1167.1	3.386	1.1325	4.8252
1147.1	7.95	4.53	3.388	1125.0	500.0	1147.1	3.388	1.1145	4.9690
1127.1	7.96	4.54	3.391	1125.0	500.0	1127.1	3.391	1.0965	5.1106
1107.1	7.97	4.54	3.393	1125.0	500.0	1107.1	3.393	1.0786	5.2499
1087.1	7.98	4.54	3.395	1125.0	500.0	1087.1	3.395	1.0606	5.3869
1067.1	7.99	4.55	3.397	1125.0	500.0	1067.1	3.397	1.0427	5.5215
1047.1	8.00	4.55	3.398	1125.0	500.0	1047.1	3.398	1.0249	5.6539
1027.1	8.01	4.56	3.400	1125.0	500.0	1027.1	3.400	1.0070	5.7838
1002.0	8.02	4.56	3.403	1125.0	500.0	1002.0	3.403	0.9847	5.9436
987.1	8.03	4.57	3.404	1125.0	500.0	987.1	3.404	0.9715	6.0367
961.7	8.04	4.57	3.406	675.0	300.0	961.7	3.406	0.9490	6.1922
947.1	8.05	4.57	3.408	675.0	300.0	947.1	3.408	0.9361	6.2798
927.1	8.06	4.58	3.409	675.0	300.0	927.1	3.409	0.9185	6.3977
907.1	8.07	4.58	3.411	675.0	300.0	907.1	3.411	0.9010	6.5132
887.1	8.08	4.58	3.413	675.0	300.0	887.1	3.413	0.8835	6.6262
867.1	8.08	4.59	3.414	675.0	300.0	867.1	3.414	0.8662	6.7367
847.1	8.09	4.59	3.416	675.0	300.0	847.1	3.416	0.8489	6.8446
827.1	8.10	4.59	3.417	675.0	300.0	827.1	3.417	0.8318	6.9500
807.1	8.11	4.60	3.419	675.0	300.0	807.1	3.419	0.8147	7.0529
787.1	8.12	4.60	3.420	675.0	300.0	787.1	3.420	0.7978	7.1531
767.1	8.12	4.60	3.421	675.0	300.0	767.1	3.421	0.7811	7.2508
747.1	8.13	4.61	3.423	675.0	300.0	747.1	3.423	0.7645	7.3458
727.1	8.14	4.61	3.424	675.0	300.0	727.1	3.424	0.7481	7.4382
707.1	8.14	4.61	3.425	675.0	300.0	707.1	3.425	0.7320	7.5280
687.1	8.15	4.61	3.427	675.0	300.0	687.1	3.427	0.7160	7.6150
667.1	8.16	4.62	3.428	675.0	300.0	667.1	3.428	0.7004	7.6992
647.1	8.16	4.62	3.429	675.0	300.0	647.1	3.429	0.6850	7.7808
627.1	8.17	4.62	3.430	675.0	300.0	627.1	3.430	0.6700	7.8595
607.1	8.18	4.62	3.431	675.0	300.0	607.1	3.431	0.6554	7.9354
587.1	8.18	4.62	3.433	675.0	300.0	587.1	3.433	0.6413	8.0085
567.1	8.19	4.63	3.434	675.0	300.0	567.1	3.434	0.6277	8.0786
547.1	8.19	4.63	3.435	675.0	300.0	547.1	3.435	0.6147	8.1458
527.1	8.20	4.63	3.436	675.0	300.0	527.1	3.436	0.6024	8.2100
507.1	8.20	4.63	3.437	675.0	300.0	507.1	3.437	0.5909	8.2711
487.1	8.21	4.63	3.438	675.0	300.0	487.1	3.438	0.5804	8.3291
467.1	8.21	4.63	3.438	675.0	300.0	467.1	3.438	0.5710	8.3839
447.1	8.22	4.63	3.439	675.0	300.0	447.1	3.439	0.5629	8.4353
427.1	8.22	4.64	3.440	675.0	300.0	427.1	3.440	0.5564	8.4834
407.1	8.23	4.64	3.441	675.0	300.0	407.1	3.441	0.5518	8.5279
387.1	8.23	4.64	3.442	675.0	300.0	387.1	3.442	0.5495	8.5687
380.0	8.23	4.64	3.442	675.0	300.0	380.0	3.442	0.5494	8.5823
380.0	?	?	5.171	10000.0	10000.0	380.0	5.171	0.5494	8.5823
360.0	?	?	5.171	10000.0	10000.0	360.0	5.171	0.5205	8.6929
340.0	?	?	5.171	10000.0	10000.0	340.0	5.171	0.4915	8.7976
320.0	?	?	5.171	10000.0	10000.0	320.0	5.171	0.4626	8.8963
300.0	?	?	5.171	10000.0	10000.0	300.0	5.171	0.4337	8.9890
280.0	?	?	5.171	10000.0	10000.0	280.0	5.171	0.4048	9.0757
260.0	?	?	5.171	10000.0	10000.0	260.0	5.171	0.3759	9.1565
240.0	?	?	5.171	10000.0	10000.0	240.0	5.171	0.3470	9.2312
220.0	?	?	5.171	10000.0	10000.0	220.0	5.171	0.3181	9.3000
200.0	?	?	5.171	10000.0	10000.0	200.0	5.171	0.2891	9.3628
180.0	?	?	5.171	10000.0	10000.0	180.0	5.171	0.2602	9.4196
160.0	?	?	5.171	10000.0	10000.0	160.0	5.171	0.2313	9.4705
140.0	?	?	5.171	10000.0	10000.0	140.0	5.171	0.2024	9.5153
120.0	?	?	5.171	10000.0	10000.0	120.0	5.171	0.1735	9.5542
100.0	?	?	5.171	10000.0	10000.0	100.0	5.171	0.1446	9.5871
80.0	?	?	5.171	10000.0	10000.0	80.0	5.171	0.1157	9.6140
60.0	?	?	5.171	10000.0	10000.0	60.0	5.171	0.0867	9.6349



## 745 7. Conclusion

746 We have constructed a preliminary reference model of the Moon based on  
747 a priori crustal structure, physical constraints on density and seismic veloc-  
748 ities variations with depth, by fitting both seismological and geodesic data.  
749 The core radius is determined from the detection of transversely polarized  
750 core reflected S wave from a low number of deep moonquakes properly lo-  
751 cated and presenting high signal to noise ratio. The VPREMOON model  
752 constrains the core size to  $380\pm 40$  km radius and average density to  $5.2\pm 1.0$   
753  $\text{kg/cm}^3$ , and favours a liquid outer core. It constitutes the first reference  
754 model including simultaneously physical constraints, geodesic and seismo-  
755 logical observations, and detection of S waves reflected on the lunar core.  
756 However, the internal structure of the lunar core remains largely unknown,  
757 and the model is still characterized by rather strong uncertainties on the  
758 different parameters owing to the paucity of available data.  
759 The constraints on the core density are strongly related to geodesic param-  
760 eters such as the polar moment of inertia of the Moon, but also to the average  
761 crustal structure. The average crustal thickness is fixed in our model, but  
762 its variation can change significantly the polar moment of inertia budget of  
763 the planet, and consequently the core density obtained. Further constraints  
764 brought by SELENE and GRAIL missions on these parameters will indirectly  
765 strongly constrain the average core density, and the radius of the inner core  
766 which is expected for thermodynamical reasons (Wieczorek et al., 2006), and  
767 for which a seismic signature has been suggested by Weber et al. (2011).  
768 Our model relies on the hypotheses of homogeneity and adiabaticity of the  
769 lunar mantle. Consequently, radial and lateral deviations from this model,  
770 that may eventually be detected by future lunar seismometers, will provide  
771 additional constraints on the internal dynamics of the lunar interior. In par-  
772 ticular, a high temperature gradient or partial melt inside the upper and  
773 lower boundary layers of the mantle may strongly modify seismic velocities  
774 and density in these regions. Both the very broad band planetary seismome-  
775 ters developed in the last decades (Lognonné et al., 1996, 2000; Lognonné,  
776 2005) and future lunar geophysical stations, such as SELENE2 (Tanaka et al.,  
777 2008) and Lunette/ILN (Neal et al., 2010) will provide crucial additional data  
778 to further improve our knowledge of the lunar interior.

779 **8. acknowledgments**

780 We acknowledge Vadim Monteiller for helpful discussions concerning quake  
781 relocation methods. This study was supported by Centre National d'Etudes  
782 Spatiales (CNES) research projects, Programme National de Planétologie  
783 (PNP) of CNRS-INSU, PRES "Université de Toulouse" (Toulouse Univer-  
784 sity) and Campus Spatial Paris Diderot (IPGP contribution number XXX).  
785 We thank the two anonymous reviewers for improving the paper by their  
786 constructive comments.

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