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Error determination of lunar interior structure by lunar geodetic data on seismic restriction

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ABSTRACT

In this study, we investigated how well we can determine the lunar interior structure using available geodetic and seismic data based on the linear inverse method. We also evaluated how we can improve our knowledge of the lunar interior structure using geophysical data obtained in future lunar geodetic and seismic explorations. A posteriori errors of the lunar interior parameters determined from geodetic data obtained from the Japanese SELENE mission and seismic data obtained from the Apollo missions indicate that the lunar core size and density cannot be determined with sufficient accuracy to reveal core composition. We quantitatively showed that accuracies of the determination of core parameters will be improved by better determination of the Love number k_2 or h_2. This improvement will be achieved by the analysis of new gravity data obtained by the NASA GRAIL mission or our planned new Very Long Baseline Interferometry experiment on the Japanese SELENE-2 mission. This will enable us to determine the core size with an approximately 10% error and the core density with an approximately 25% error and improve our knowledge of the core. We will also be able to further reduce the errors in core density by applying future seismic network explorations and obtain information on the composition of the lunar core and its inner structure.

1. Introduction

Knowledge of the interior structures of planetary bodies is important for revealing the composition of the planets and constraining their origin and evolution. The Moon is the only planetary body with an interior that has been investigated by both geodetic and seismic methods except the Earth. Recent analysis of seismic and geodetic data has constructed a new lunar interior model: the very preliminary reference Moon model (VPREMOON) (Garcia et al., 2011). This model indicates the presence of a possible lunar liquid core. Weber et al. (2011) described the detection of reflected seismic phases from the possible core/mantle boundary and constrained the size of the lunar Fe core. However, there are still large uncertainties about the lunar deep structure, including the core, because there is a trade-off between the weakly constrained lower mantle and the core size from reflected phases. In particular, we do not have any definite information on the interior of the core (Garcia et al., 2011). The thermal state and composition (Fe or FeS) of the lunar central core are very important factors for constraining the thermal evolution and origin of the Moon. Further investigation of the lunar deep structure is required.

Both seismic and geodetic data are useful for investigations of the lunar interior structure because these data provide density and elastic information about the interior (Khan and Mosegaard, 2005; Khan et al., 2006; Garcia et al., 2011). However, we do not have definite knowledge about how well we can determine the interior structure using geophysical data. To further progress our understanding the lunar interior and to design new lunar geophysical exploration, we need to know how accurate geophysical data should be so as to improve our knowledge of the lunar interior structure with the necessary accuracy.

In this study, we reveal the relation between the errors in the geophysical data and the resulting accuracy of the lunar interior structure derived from the data, with special emphasis on the geodetic data. First, we evaluate how well we can determine the lunar interior structure, including the core, using geodetic data obtained from the SELENE mission and seismic data obtained from the Apollo missions. Then, we discuss expectations for how we can improve the errors of the lunar interior structure by lunar geophysical experiments after SELENE.

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2. Method

We evaluate the a posteriori errors of the model parameters related to the lunar interior structure estimated from given geophysical data errors based on the linear inverse method. Some studies (e.g., Khan and Mosegaard, 2005; Garcia et al., 2011) derived parameters of the lunar interior structure by applying the Markov-chain Monte Carlo method to solve the inverse problem. However, our goal is to derive the a posteriori errors of lunar interior parameters, not the values of the parameters themselves. Other studies, such as that of Garcia et al. (2011), require actual geophysical data to determine the interior structure; however, this study does not need any actual data because the a posteriori errors of models can be evaluated from only the data errors. Our method is useful to evaluate the data needed and the accuracy of those data to determine the model parameters with required accuracy in future measurements. It is also useful to validate the results and accuracies derived from previous geophysical studies, such as those of Khan and Mosegaard (2005).

Herein, we describe a method to evaluate the accuracy of determination of the lunar interior structure when the errors of the input data are given. The model parameters to be determined and the data are related by this equation (Tarantola, 2005; Yamada et al., 2011):

$$\Delta\vec{d} = G\Delta\vec{m} \tag{1}$$

where Δd is the data variation corresponding to variation in the model parameter Δm, and G is the data kernel. In the linear inverse problem, we will determine the model parameters to minimize the cost function $J(\vec{m})$ such that:

$$J(\vec{m}) = \|\Delta\vec{d} - G\Delta\vec{m}\|^2 + \lambda\|L\vec{m}\|^2 \tag{2}$$

where λ is a regularization parameter, and L is the Laplacian operator. The Laplacian operator constrains the model parameters to have minimum differences among neighboring parameters on the value of the regularization parameter for the underdetermined condition (Menke, 1989). Then, we can derive the a posteriori covariance matrix of the model parameter C_m^p from:

$$C_m^p = \left(G^T C_d^{-1} G + \lambda L^T L\right)^{-1} \tag{3}$$

where C_d is the a priori covariance matrix of the data, and the diagonal components consist of geophysical data errors. The model resolution matrix R is also represented as:

$$R = C_m^p G^T C_d^{-1} G \tag{4}$$

We can derive the accuracy of determination of the lunar interior structure from the diagonal components of the a posteriori covariance matrix of model parameters C_m^p, because the components consist of the a posteriori error of each model parameter. Eqs. (3 and 4) indicate that we can determine the a posteriori errors if we can estimate the data errors as components of C_d, even if we do not have actual data.

3. Data

In this section, we describe the available geodetic and seismic data and their data errors to evaluate the a posteriori errors of the lunar interior structure from Eq. (3).

3.1. Geodetic data

Past lunar geodetic exploration, such as a sequence of gravity explorations through satellite tracking and lunar laser ranging (LLR), have provided us with useful information, such as the tidal Love numbers and the moment of inertia. The second-degree tidal Love numbers k_2 and h_2 are important parameters that indicate the elasticity of the lunar interior, and their accuracies are continuously being improved through gravity and LLR data analysis (e.g., Goossens et al., 2011; Williams et al., 2011, 2013; Konopliv et al., 2013). The moment of inertia and lunar mass are also useful information for the determination of the density structure. These four types of geodetic data can be used the inversion to derive the lunar interior structure (e.g., Khan and Mosegaard, 2005).

The accuracies of the tidal Love number k_2 and the moment of inertia can be made better with the improvement of the coefficients of the gravity field through satellite tracking data analysis. First, we consider the gravity results of the Japanese lunar orbital mission SELENE. The lunar explorer SELENE was launched in September 2007 and continued exploration by remote sensing until June 2009. During the exploration, a small relay satellite was used, which relayed the Doppler tracking signal of the main satellite when it was on the lunar far side. This observation provided us with the first accurate gravity information for the lunar far side (Namiki et al., 2009). Then, a better estimation of the lunar gravity field was achieved through the precise orbital determination of the sub-satellites using the differential Very Long Baseline Interferometry (VLBI) method, receiving signals transmitted from radio sources on the sub-satellites by multiple ground stations (Goossens et al., 2011).

Table 1 shows the values and errors for the four types of geodetic data: k_2, h_2, mean moment of inertia (MOI), and mass based on the SELENE tracking data (Goossens et al., 2011) and LLR data (we use the error of dynamical flattening as reported by Konopliv et al. (1998) to obtain the error of the mean MOI). We use the errors of four geodetic data, k_2, h_2, mean MOI, and mass, listed in Table 1 as diagonal components of C_d to evaluate the a posteriori errors of the lunar interior structure from Eq. (3).

3.2. Seismic data

It is usually difficult to resolve the interior structure using only four types of geodetic data. Seismic data are available for the identification of boundaries among density variations in the interior. The only lunar seismic data that we can use were obtained from the Apollo seismic experiments (e.g., Nakamura et al., 1982). Some researchers have investigated the lunar interior structure using the seismic data obtained from the Apollo seismic network, which consisted of four stations (Apollo 12, 14, 15, and 16) (e.g., Khan and Mosegaard, 2002; Lognonné et al., 2003).

We use four types of lunar seismic events to evaluate the lunar interior structure: they are deep moonquakes, shallow moonquakes, meteoroid impacts, and artificial impacts (e.g., Nakamura et al., 1982). For deep moonquakes, we select seismic events originating from 15 active sources that were accurately located by Nakamura (2005). Selected deep events have also been used in other studies to investigate the lunar interior structure (Lognonné et al., 2003; Gagnepain-Beyneix et al., 2006). Shallow moonquakes and meteoroid impacts are useful for obtaining information on the lunar shallow structure and crustal thickness (e.g., Chenet et al., 2006). Artificial impacts were generated from the impacts of the lunar modules and the upper stage S-IVB of the Saturn V rockets; these have been used to investigate the lunar surface and crustal structures (e.g., Cooper et al., 1974). We used 8 shallow events, 19 meteoroid impacts, and 8 artificial impacts that have been located by some studies (Gagnepain-Beyneix et al., 2006; Garcia et al., 2011).

Finally, we use 265 travel time data for P and S phases from Apollo data to evaluate the accuracy of determination of lunar interior structures. The data errors of travel times are given as reading errors of the arrival time. The observed lunar seismic events are