DETERMINATION OF THE LUNAR k_2 LOVE NUMBER FROM SATELLITE TRACKING DATA. S. Goossens and K. Matsumoto, National Astronomical Observatory of Japan, RISE Project Office, 2-12 Hoshigaoka, Mizusawa-ward, Oshu-city, 023-0861 Iwate, Japan (sander@miz.nao.ac.jp)

Introduction: Tides are raised on the Moon by the gravitational attraction of the Earth and Sun. The Moon's elastic response to these tides is described by Love numbers, of which the second degree tides are the strongest [1]. The influence on the gravitational potential due to these tides is described by the potential Love number k_2. By taking this tidal potential into account in the processing of satellite tracking data, the value for k_2 can be determined. This has been done in the past for Venus [2] and Mars (e.g. [3]). For the Moon, one such spacecraft-based result also exists [4], k_2 = 0.026, although the main means of determining the lunar k_2 have come from lunar laser ranging (e.g. [5]). Recent solutions for k_2 from lunar laser ranging are around 0.0210 [6].

The size and composition of the lunar core are not yet fully determined. Recent analysis indicates a molten core [7] with the possibility of a solid inner core [6]. The k_2 Love number can help to constrain models of the deep lunar interior, but the uncertainty at this moment is close to the precision required to distinguish between models [8].

The SELENE mission [9], launched on September 14, 2007, will provide data to study the lunar interior. By means of 4-way Doppler tracking between the main and a relay satellite, the first global tracking data for the Moon will be obtained. A differential VLBI experiment is also carried out using the two subsatellites. Simulations show that the lower spherical harmonical degrees of the gravity field model expansion are expected to be improved up to one order of magnitude [10] (see also Figure 1). This also means that the current estimate for k_2 is expected to improve. Prior to using data from SELENE, the goal of this research was to determine the k_2 Love number from existing data and investigate its sensitivity with respect to the different data sets.

Data: Tracking data used consisted of Doppler data from the Lunar Orbiters (LO) I-V, the Apollo 15 and 16 subsatellites, Clementine and Lunar Prospector (LP). Some tracking data from the SMART-1 spacecraft were also included, albeit very little (spanning January 2006 and May 29 – June 2, 2006).

Data processing: These data were processed using the GEODYN II [11] software to create the normal equations for the least squares solution to estimate the wanted parameters. This system of normal equations was then combined and solved for using the accompanying program SOLVE.

Data are divided into arcs, continuous time spans, where arc length is a compromise between sensitivity and limiting dynamical errors. Typical arc lengths were two days, although, especially for the historical data such as LO and the Apollo subsatellites, much shorter arcs were used as well. For LO, this was mainly due to the many manoeuvres on the satellites, inducing spurious signal on the data residuals, thus severely limiting the usable arc length. For Clementine, several arcs spanning 10 days were included.

Force modeling on the satellites consisted of the LP150Q model [12] as a priori gravity field. The DE403 ephemeris were adopted for the computation of third-body perturbations, as well as the definition of the lunar librations and coordinate system. Solar radiation pressure was modeled as a cannonball model.

Estimated parameters included the gravity field up to degree and order 40, the lunar Love number k_2 and the lunar *GM* as common parameters; arc-dependent parameters were the initial state vector at epoch, biases on the data, a solar radiation pressure coefficient and, in the case of Clementine and Lunar Prospector, empirical accelerations with a signature of 1 cycle-per-orbital-revolution (cpr) in the along and cross track directions along the orbit.

Data weights have been reported to be of great influence on the satellite-derived value for k_2 [4]. Here, LO and Apollo subsatellite data were generally weighted at 1.5 mm/s, unless arcs had an exceptionally high RMS of data fit, in which case they received weights of 6-9 mm/s. Clementine data were weighted at 1 mm/s, and so were SMART-1 data. For LP, the extended mission (which lasted from January-July 31, 1999) had a lower altitude compared to the nominal mission, of 40 km vs 100 km. The extended mission consisted further of two parts; one with the perilune on the near side (Jan-April, 1999) and one with the perilune on the far side (May-July, 1999). This resulted in different levels of data noise. The nominal mission was weighted at 1 mm/s. For the extended mission, the last part was always weighted at 6 mm/s. The first part was also weighted at 6 mm/s, but solutions with a data weight of 3 mm/s were also computed.

Results: Table 1 lists results for k_2 from the use of several different data sets and orbit parametrisation, as indicated. All solutions use a Kaula rule of 36 x $10^{-5}/l^2$ to solve for the gravity field, with l the degree. For LP and Clementine, 1 cpr along and cross track accelerations are included, unless indicated otherwise. The LP extended mission data for May-July are always weighted at 6 mm/s; the data for Jan-April are also weighted at 6 mm/s, unless a different data weight is listed.

Data and parametrisation	**Value for k_2**
Lunar Prospector only	0.0205 ± 0.0076
LP, 75x75 gravity field estimated	0.0207 ± 0.0077
All data	0.0213 ± 0.0075
All, without LP extended data	0.0290 ± 0.0081
All, without Clementine long arcs	0.0209 ± 0.0074
All, without Kaula constraint	0.0213 ± 0.0075
All, no 1cpr accelerations LP	0.0244 ± 0.0008
All, weight ext. Jan-April 3 mm/s	0.0118 ± 0.0072
All, 1 cpr rad/cr, weight 3 mm/s	0.0194 ± 0.0072
All, no acc, weight J-A 3 mm/s	0.0238 ± 0.0078

Table 1: Results for the k_2 Love number from different data sets. Note that the formal errors are ten sigma.

Table 1 shows that the results for k_2 are strongly dominated by the LP data, as expected. The solutions are sensitive to data weights. Remarkably, if the weight for the period Jan-April, 1999 is taken as 3 mm/s, and the 1-cpr accelerations are included, the estimate for k_2 becomes very low, at 0.0118. This seems unlikely in the light of the other solutions for k_2, or those determined by lunar laser ranging (e.g. [7]).

The 1 cpr empirical accelerations in the parametrisation were chosen in order to compensate for non-conservative force mismodelling. If these accelerations are left out, the estimate for the solar radiation pressure coefficient starts to vary, indicating that the accelerations indeed influence the non-conservative force modelling [13]. Furthermore, when the accelerations are not taken along in the parametrisation of the satellite orbit, the degree variances for the solved-for gravity field are also higher, see Figure 1. Because the data fit improves with the accelerations taken along, and the variability in the solar radiation pressure coefficient is reduced, the best estimate here is taken from the result using all the data, namely k_2 = 0.0213 ± 0.0075, using ten times the formal error to accommodate for systematical errors.

Discussion: Roughly, the solutions for k_2 vary between 0.020 and 0.025. The best estimate chosen here, 0.0213, is closer to the results of lunar laser ranging than the previous satellite-derived estimate. The same data were used here, with the exception of some SMART-1 tracking data, and data from one station for the Clementine spacecraft, so the formal error can't be

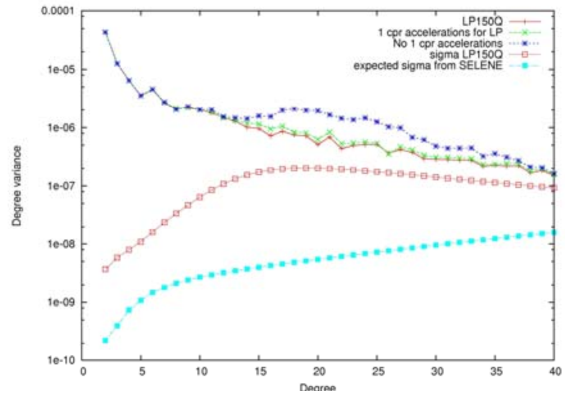

Figure 1: Degree variances of gravity field solutions with different parametrisations. Expected results from SELENE simulations (including 2-way, 4-way and VLBI data) are also shown.

improved upon. In order to determine whether or not there is a solid inner core, the uncertainty on k_2 needs to be improved further [6].

Outlook: With the launch of SELENE (also nicknamed KAGUYA), the first global tracking data of the Moon will become available, improving the lower degrees. Further improvement is expected from the differential VLBI experiment, which yields precise data and a sensitivity to a direction perpendicular to the line-of-sight direction [14]. Furthermore, since the two subsatellites are free-flying satellites, it is expected that longer arc lengths can be used when processing data from these satellites, which yields an increased sensitivity to the lower degrees and the lunar Love number as well. Thus, as tracking data are collected from SELENE, further investigation into the lunar Love number will also be conducted.

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