A DYNAMICALLY ACTIVE MOON – LUNAR FREE LIBRATIONS AND EXCITATION MECHANISMS.

N. Rambaux, J. G. Williams and D. H. Boggs, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 (e-mail Nicolas.Rambaux@ jpl.nasa.gov, James.G.Williams@jpl.nasa.gov).

Introduction: The lunar motion has been measured accurately for 38 years with Lunar Laser Ranging [1,2,3]. Today, the time-span of several decades and the accuracy of a few centimeters allow one to identify and characterize some geophysical mechanisms that influence the rotational motion.

The three dimensional rotational motion of the Moon is characterized by the physical librations, the departure from uniform rotational motion. These librations can be classified as two types: (i) Forced librations arise from time-varying torques on the lunar figure due to the Earth and the Sun. Their amplitudes result mainly from the gravitational torques with some modification by tides. (ii) Free librations are the natural rotation modes of the solid Moon and they are implicit in the equations of motion for the rotation. The amplitudes of the free librations may be excited by geophysical or dynamical mechanisms [4,5].

Our objective is to first determine in the LLR observations the presence of the free modes and second to propose possible mechanisms that excite these free modes.

Free modes: Classically, there are three modes of free librations for a rigid Moon. One is in longitude, parallel to the equatorial plane of the Moon, with a period of 2.9 years, and a second one in latitude, motion of the axis normal to the lunar equatorial plane, with a period around 81 years. These two modes are related to the synchronous spin-orbit motion of the Moon and the periods are given in the inertial reference frame [4,5].

The third mode of free libration is related to the rotation of the axis of figure about the rotation axis. It is analogous to the Earth's Chandler wobble and has a period around 75 years in the lunar reference frame, i.e around 27 days in the inertial reference frame [4].

Each proper mode is characterized by a damping time scale. Based on the tide and core dissipation results given in [6], the damping times are $2x10^4$ yr for the longitude mode, $1.5x10^5$ yr for the 81 yr latitude mode, and $1x10^6$ yr for the wobble mode As a consequence, the observational detection of free librations requires recent excitation mechanisms compared to the damping times.

Fit strategy: Along with the orbit and Earth-related effects, the three-dimensional lunar rotation is fit to Lunar Laser Ranging data with adjustable parameters for moments of inertia, gravity field, tides, dissipation, interaction with a fluid core, and initial conditions for both solid mantle and fluid core [1,6]. The initial conditions and constants are used to make a numerical integration of the lunar rotation jointly with the orbits of the Moon and planets. The result of the integration is a file of very accurate Euler angles versus time. The free librations are extracted from the Euler angles with a fit of analytical terms.

The lunar rotation exhibits combined forced and free librations and we determine in the same fit the two sets of librations. The periods of the forced librations are known because they arise from 1) Earth-Moon-Sun effects, and their periods are related to the Delaunay arguments of lunar theory [7], and 2) planetary effects that contribute to the spectrum of terms [8].

The amplitudes of periodic Fourier terms can be variable. This can be due to the eccentricity of the Earth-Moon orbit around the Sun, which varies with time and alters the amplitude of the librations. We represent these variations by introducing Poisson terms, linear terms in time in the amplitudes.

The analytical form of the librations is thus assumed to be composed of Fourier and Poisson series (with adjustable frequencies during the fit) and polynomial coefficients. The polynomial coefficients are used to represent small corrections to the uniform rotation of the Moon and very long period effects.

We used a least-square method to fit the formal solution to the libration angles. The scheme is iterative in order to converge toward robust values. We also estimate the postfit residuals and can generate Fourier spectra. The maximum post-fit residual is 0.1 arcseconds.

Longitude mode: Figure 1 shows the resulting spectrum composed of forced and free librations for the lunar libration in longitude. The three largest libration amplitudes result from the Earth-Moon motion around the Sun (365.25 days), the anomalistic orbit period of the Moon around the Earth (27.55 days), and half the argument of perigee period (1095.17 days). The free libration is the 10^{th} largest libration with an amplitude around 1.8 arcseconds. The period is determined to be 1056.20 days. The fit longitude "free libration" is a combination of the real free libration and two forced terms that are too close in period to separate (1056.80 and 1056.30 days). In addition, the amplitudes of forced terms such as those at 1069.24 days and 1095.17 days, the latter is the third largest longitude libration amplitude, are correlated with the amplitude of the free libration.

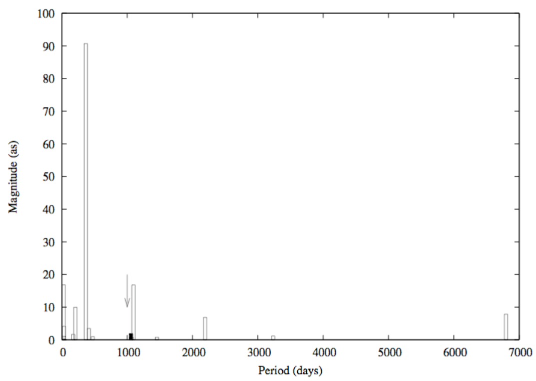

Fig1: Spectrum of the libration in longitude. The presence of the free libration is indicated by the arrow and the black box. The frequency of the free libration is 1056.2 days.

Latitude mode: The free latitude mode of the Moon is very small and therefore uncertain. If the presence of this amplitude is confirmed, it does not exceed a few tens of milliarcseconds.

Wobble mode: The last mode is more easily expressed in the selenographic reference system. In this case, the body polar axis of the Moon describes a small cone of semi-axes 8.2 arcseconds by 3.3 arcseconds with a period of 75 years with respect to the rotation axis. Contrary to the situation with the longitude mode, there are no nearby forced frequencies close to this mode and its amplitude is decorrelated from the other librations.

Possible excitation mechanisms: Some possible mechanisms have been explored in the past without satisfactory explanation. It has been shown that a recent meteoritic impact is an unlikely source of such excitation [9]. Eckhardt [10] proposed an excitation process related to a resonance event between the longitude proper mode (of 2.9 years) and close forced frequencies. During the evolution of the lunar orbit, the free frequency changes slowly and can become equal to a forced period in longitude. However, the mechanism excites only the libration in longitude mode. Yoder [11] proposed an alternative mechanism, based on turbulent fluid core interaction, to excite the wobble mode.

The accurate determination of the amplitudes of the free librations is a motivation to understand how the presence of a fluid core inside the Moon could excite free modes.

Acknowledgements: The research described in this abstract was carried out at the Jet Propulsion Laboratory of the California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

This research was supported by an appointment to the NASA Postdoctoral Program at Jet Propulsion Laboratory of the California Institute of Technology, administrated by Oak Ridge Associated Universities through a contract with National Aeronautics and Space Administration.

References: [1] Williams J. G. et al. (2001) *J. Geophys. Res., 106,* 27,933-27,968. [2] Dickey J. O. et al. (1994) *Science*, *265*, 482-490. [3] Williams J. G. and Dickey J. O. (2003) Proceedings of 13th International Workshop on Laser Ranging, Washington, D. C.,http://cddisa.gsfc.nasa.gov/lw13/lw_proceedings.html. [4] Newhall X X and Williams J. G. (1997) *Celestial Mechanics and Dynamical Astronomy*, *66*, 21-30. [5] Bois, E. (1995) *Astron. and Astrophys., 296,* 850-857. [6] Williams J. G. et al. (2008) Abstract No. 1484 of *Lunar and Planetary Science Conference XXXIX*. [7] Chapront-Touzé M. and Chapront J. (1983) *Astron. Astrophys., 124*, 50-62. [8] Bretagnon P. (1982) *Astron. Astrophys., 114*, 278. [9] Peale S. (1975) *Journal of Geophysical Research, 80,* 4939-4946.. [10] Eckhardt D. (1993) *Celestial Mechanics and Dynamical Astronomy* **57**, 307-324. [11] Yoder C. F. (1981) *Phil. Trans. R. Soc. Lond. A* **303**, 327-338.