# Influence of Earth-Moon orbit geometry on deep moonquake occurrence times

Bruce G. Bills[1,2], Renee Bulow[3], and Catherine L. Johnson[2,4],
[1]NASA/GSFC, Greenbelt, Maryland, [2] Scripps Institution of Oceanography, La Jolla, California,
[3]Institute de Physique du Globe de Paris, Paris, France, [4]Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada

**Introduction:** We present a new model for the times of deep focus moonquakes. This model assumes that, for each deep moonquake cluster, there is a unique linear combination of orbital parameters which is favorable for moonquake occurrence. Because of solar perturbations, the lunar orbit does not exhibit simply periodic behavior.

Several deep moonquake clusters exhibit relatively simple, quasi-periodic behavior, with favored periods being either the anomalistic month (27.5545 days), which controls Earth-Moon distance and sub-Earth longitude, or the nodical month (27.2122 days), which controls sub-Earth latitude. Even in these cases, our model performs better, in terms of residual variance (Fisher-Snedecor F ratio), than a purely periodic model, and has the advantage of providing better insight into the cause of the temporal pattern.

**Background:** One of the most intriguing findings of the Apollo Lunar Seismic Experiment [1] was that many of the deep focus events are related to tides raised on the Moon by the Earth [2,3,4]. However, despite considerable past effort [5,6,7,8], many aspects of the deep moonquake situation are still only rather poorly understood. One reason for the continuing difficulty in producing realistic models of the deep moonquake tidal triggering process is that the limited extent and number of the Apollo seismic stations made event location determination difficult. In addition, significant scattering within the Moon made the determination of fault plane orientations even more difficult [9,10].

As a result of these uncertainties in moonquake source parameters, most of the more definitive tests which have been applied to cases of tidal triggering of Earthquakes [11-18] are not feasibly applicable at the Moon. If, for example, the location and orientation of the fault plane at a deep moonquake source were known, it would be a simple matter to project the time-varying tidal stress tensor at that location onto the fault plane, and see whether the resolved shear and normal stresses at event times had repeatable patterns. However, uncertainties in source locations make the tidal stress tensor calculations somewhat uncertain, and the absence of clear seismological evidence for fault plane orientations within the Moon severely limits the critical step of projecting the tensor onto the plane.

Given the difficulty in locating and orienting deep moonquake sources, we are motivated to consider an alternative strategy, which depends only upon the very well known relative position and velocity of the Earth, as seen from the Moon. If there were a preferred tidal stress condition, on a deep source fault plane, then we would expect that those conditions would be met only when the tidal stress tensor had the appropriate value. As the tidal stress tensor depends upon both the source (Earth) and receiver (within the Moon) locations, tidal forcing will depend diagnostically upon the relative Earth-Moon position variations. Thus a preferred tidal stress state for triggering of deep moonquakes implies a preferred combination of position and/or velocity of the tide raising body.

The primary objective of the current study is to test the hypothesis that there is, at each deep moonquake cluster, a linear combination of Earth-Moon position and velocity components which is nearly constant at the times of the seismic events at that cluster.

**Method:** Our approach to exploring the connection between orbital parameters and moonquake cluster event times has several steps. The early steps are essentially an empirical orthogonal function (EOF) analysis [19]. We begin by tabulating the values of position and velocity of the Earth, with respect to the Moon, at 1 day intervals over the time span 17 April 1969 to 13 May 1978 (3314 days). The parameters are Earth-Moon distance ($r_e$), sub-Earth latitude ($\theta_e$), sub-Earth longitude ($\phi_e$), and rates of change of these three. The position values were obtained from the USNO software MICA, and the rates were obtained via differentiation of a cubic-spline interpolation of the position values.

It is convenient to use orbital parameters with identical dimensions and comparable dynamic ranges. We thus replace the actual Earth-Moon distance $r_e$, with a normalized deviation from the mean value,

$$s_e = (r_e - \bar{r}_e) / \bar{r}_e$$

For a given cluster, we begin by evaluating the 6 orbital parameters at the event times for the cluster:

$$p_j = \{s_e[t_j], \theta_e[t_j], \phi_e[t_j], \dot{s}_e[t_j], \dot{\theta}_e[t_j], \dot{\phi}_e[t_j]\}$$

where over-dots indicate time derivatives. We then compute the correlation matrix for those 6 time series, and determine the corresponding eigenvectors.. These eigenvectors ($f_1$, .., $f_6$) represent the linear combinations of the input time series which are orthogonal, when evaluated at the event times. Multiplying each of the eigenvectors by the input parameter values, we thus obtain orthogonalized time series.

$$F_i[t_j] = f_i \cdot p_j$$

We then compute the coefficients in the series

$$g[t] = \sum_i \alpha_i F_i[t]$$

which best represent our target function g = 1. These coefficients are obtained in the usual way, by projecting the basis functions onto the target function, and normalizing:

$$\alpha_i = (F_i \cdot g)/(F_i \cdot F)$$

When we have the coefficients, we then evaluate the function g[t] at both event times and at the uniform 1 day time steps. The background value of the function, at 1 day time steps, generally has the appearance of a sum of sinusoidal oscillations with several closely spaced frequencies, and associated amplitude modulation.

To remove the effects of oscillating basis functions and amplitude modulation, we then demodulate the signals, and compute the arcsine of the demodulated values. The demodulation removes longer period variations in amplitude, and the arcsine transformation changes sinusoidal variations into piece-wise linear variations. When those steps are completed, we can often find a good approximation to a constant target signal.

**Results:** In the space available here, we can only present a single example of the application of our algorithm. The largest cluster, in terms of number of identified events, is A1 (located at {lat,lon} = {-14°, -37°}) with 443 events [8]. It shows influence of both anomalistic and nodical periods. The minimum value of residual variance ratio obtained under the assumption of purely periodic behavior is 40.4%, with a period of 27.19 days. A secondary local minimum, of 40.6%, occurs at a period of 27.58 days. Our orbital fitting solution yields a minimum variance ratio of 33.3%, with parameter weights of {67.3, 34.9, -34.3}% for position and { -0.2, -23.2, 50.6}% for velocity.

Figure 1 shows event times (red) and background times (black) modulo 27.19 days. Figure 2 shows the same times, but as represented in our best fitting orbital parameter linear combination

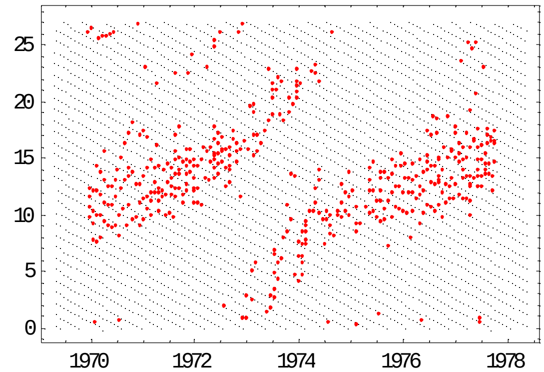

Fig 1. A1 cluster event times, modulo 27.19 days

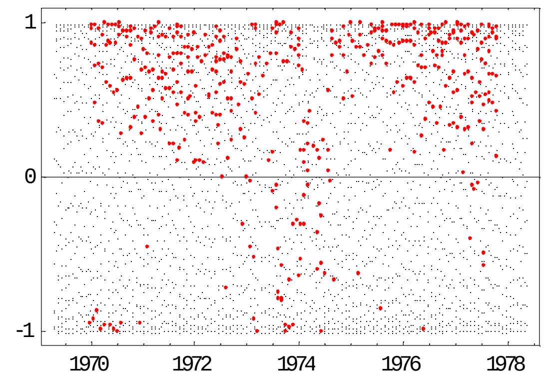

Fig 2. A1 cluster orbital parameter EOF analysis.

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