NEWTONIAN AND POST-NEWTONIAN TIDAL THEORY: VARIABLE G AND EARTHQUAKES*

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Abstract. A mathematical analysis of the Newtonian and parametrized Post-Newtonian tidal stresses is applied to tidal triggering mechanism for earthquakes. We investigate a possible correlation.

The procedure used for calculating the solid earth tidal stress is described by the Newtonian theory and the parametrized Post-Newtonian metric. We calculate tidal stress histories for earthquakes between 1908 and 1991 in Greek area. Although no significant tidal correlation was found for the entire data set, which contained earthquakes of magnitude $M \geqslant 6.0$, a fairly striking correlation was observed for an earthquake-tide correlation by computing tidal functions at the time and place of the earthquake events. A successful correlation as used in this paper means that: earthquake events occur during a certain part of the tidal cycle.

Also, we have studied a variation of the gravitational constant according to the variation of the velocity of the Earth and the uniform velocity of the Solar System with respect to a "preferred Universal rest frame".

1. Introduction

The lunar tidal potential function U_L at a test point P on the Earth's surface is defined by

$$U_L = -\frac{GM_L}{d} + \frac{GM_L}{|\bar{d} - \bar{R}|}, \tag{1}$$

where G = gravitational constant; R = radius of the Earth; M_L = mass of the Moon; d = distance from tne Earth to the Moon ($|\bar{d}| = d$); and the mass of the test body at the point P is taken as unit.

Expanding Equation (1) in powers of R/d we find that

$$U_L = -\frac{GM_L}{d} + \frac{GM_L}{d}\left[P_0(\cos\gamma) + \frac{R}{d}P_1 \times \right.$$
$$\left. \times (\cos\gamma) + \frac{R^2}{d^2}P_2(\cos\gamma) + \cdots\right]. \tag{2}$$

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where $R/d \ll 1$, $P_i(\cos\gamma)$, $i = 0, 1, 2, 3, \ldots$ are Legendre polynomials and γ is the angular separation between the sublunar point and test body at the position P.

Similarly the Solar tidal potential function U_S at the same point P is defined by

$$U_S = -\frac{GM_S}{D} + \frac{GM_S}{D}\left[P_0(\cos\Gamma) + \frac{R}{D}P_1(\cos\Gamma) + \right.$$

$$\left. + \frac{R^2}{D^2}P_2(\cos\Gamma) + \cdots\right], \qquad (3)$$

where M_S = mass of the Sun; D = distance from the Earth to the Sun; Γ = the angular separation between the subsolar point and point P.

Now, using a coordinate system that has the center of mass of the Earth as origin we get $P_1(\cos\gamma) = P_1(\cos\Gamma) = 0$.

Hence, the joint lunar and solar tidal potential function is defined by

$$U_{\mathrm{TIDAL}} = U_L + U_S = \frac{GM_L R^2}{d^3}\left[P_2(\cos\gamma) + \frac{5}{11}P_2(\cos\Gamma)\right], \qquad (4)$$

where $D \approx 400d$. That is to say a sum of periodic components.

In Equation (4) we have taken the leading first terms of the expansions (2) and (3). Also, Equation (4) can be written as

$$U_{\mathrm{TIDAL}} = \frac{1}{2}\frac{GM_L R^2}{d^3}\left[3\cos^2\gamma - 1 + \frac{5}{11}(3\cos^2\Gamma - 1)\right]. \qquad (4a)$$

2. Newtonian Tidal Theory. Tidal Triggering of Earthquakes

Now, we shall use the known relations

$$\cos\gamma = \sin\theta\sin\theta_L + \cos\theta\cos\theta_L\cos(\varphi - \varphi_L), \qquad (5)$$

$$\cos\Gamma = \sin\theta\sin\theta_S + \cos\theta\cos\theta_S\cos(\varphi - \varphi_S), \qquad (6)$$

where θ's are the latitudes and φ's are the longitudes; the test body P is at the position (R, θ, φ), the sublunar point at (R, θ_L, φ_L), and the subsolar point at (R, θ_S, φ_S).

As the Earth rotates the points (R, θ, φ), (R, θ_L, φ_L) and (R, θ_S, φ_S) move over its surface with the passage of time.

In the Newtonian framework space, using Equations (4a), (5) and (6), we get

$$U_{\mathrm{TIDAL}} = \frac{1}{2}\frac{GM_L m}{d^3}R^2\{3[\sin\theta\sin\theta_L + \cos\theta\cos\theta_L\cos(\varphi - \varphi_L)]^2 +$$

$$+ \tfrac{15}{11}[\sin\theta\sin\theta_S + \cos\theta\cos\theta_S\cos(\varphi - \varphi_S)]^2 - \tfrac{16}{11}\}, \qquad (7)$$

where m has been considered as the mass of the test body.

From Equation (7) we note a physical effect: high tides occur at time intervals of about $12^{\mathrm{h}}.42$ and low tides at times halfway between them.

In Equation (7) several of the parameters are time-dependent as the Earth rotates; the sublunar and subsolar points move over its surface; the lunar and solar distances and the celestial coordinates (e.g., right ascension and declination) change with the passage of time. Hence, U_{TIDAL} fluctuates in a complex manner.

The expression for the vertical component (directed upward) of acceleration due to the Moon and Sun is defined by

$$\bar{g} = \frac{\partial U_{\mathrm{TIDAL}}}{\partial R}\frac{\bar{R}}{R} \qquad (|\bar{R}| = R)$$

or

$$g = \frac{\partial U_{\mathrm{TIDAL}}}{\partial R} = \frac{GM_L}{d^3} R\{3[\sin\theta\sin\theta_L + \cos\theta\cos\theta_L\cos(\varphi - \varphi_L)]^2 + \\ + \tfrac{15}{11}[\sin\theta\sin\theta_S + \cos\theta\cos\theta_S\cos(\varphi - \varphi_S)]^2 - \tfrac{16}{11}\}\,. \qquad (8)$$

Equation (8) gives a change in gravity.

The tidal potential function U_{TIDAL} is investigated as a factor in producing stresses which may trigger earthquakes in an active region. This work has been done on the idea that Earth tides may trigger earthquakes. So, it can be shown on certain assumptions that the potential at any given site (R, θ, φ) on the Earth's surface is proportional to the magnitude of a bulge along the line joining Moon (and Sun) and center of the Earth, facing out toward the Moon (considered as positive) and another equal bulge at the antipodes of the sublunar point (considered as negative) (Dionysiou *et al.*, 1993).

The search for an earthquake-tide correlation is conducted by computing tidal functions at the time and place of the earthquake events. Here the events are earthquakes of magnitude $M \geqslant 6.0$ in Greek area. We believe that the use of large catalogues of earthquakes from a large geographic areas has failed to demonstrate significant tidal triggering. Therefore, in the future, we shall try any tidal correlation of earthquakes in a small region, in a certain magnitude range, or of a particular type of earthquakes (Dionysiou *et al.*, 1993).

3. Parametrized Post-Newtonian Formalism

The Newtonian gravitational constant G as measured by means of Cavendish experiments may depend on the observer's velocity relative to a Universal rest-frame. Some metric theories of gravity single out the mean rest-frame of the Universe as a preferred frame. In this work, the Solar system is assumed to be in uniform motion relative to the preferred Universal rest-frame.

The solar system's motion through the Universe is due to its (nearly circular) orbital motion around the Galaxy and the peculiar motion of the Galaxy itself.

On the other hand, if the Newtonian constant G is determined by the distribution of matter in the Universe, then it should depend on where in the Universe one is, as well as when. Particularly, as one moves from one position to another one in the Solar system, closer to the Sun and then farther away, one should see the change of the Newtonian constant. This is possible in our work, as in most metric theories of gravity but not in General Relativity.

The Parametrized Post-Newtonian (PPN) formalism (Nordtvedt and Will, 1972; and references given there) contains a set of parameters called "PPN parameters" that can be specified. These parameters, whose values vary from theory to theory have a physical or conceptual significance. When one writes in a coordinate system which moves with a velocity w relative to some "preferred frame" the PPN metric may contain additional terms which depend on w; these additional terms depend on the "PPN parameters" and may produce observable effects.

Finally, the "preferred-frame" effects give geophysical results which alter the state of stress of the Earth's lithosphere and then perhaps causes triggering of earthquakes.

4. Semidiurnal Variations in G. Tides of the Solid Earth

The semidiurnal variations in G are completely analogous to the tides produced by the Moon and the Sun, i.e., the tidal potential function U_{TIDAL} and the variation $\Delta G/G$ have the same period of 12 hr.

Following Nordtvedt and Will (1972), and references given there (i.e., using the Parametrized Post-Newtonian (PPN) formalism) and long but straightforward calculations we find retaining only term with 12-hr period that

$$\begin{aligned}\frac{\Delta G}{G} = \tfrac{1}{4}\alpha_2\{\tfrac{1}{2}w^2 \cos^2\delta \cos^2 L \cos 2(\Omega t - \epsilon - \alpha) + \\ + \tfrac{1}{2}wu \cos\delta(1 - \cos\theta)\cos^2 L \sin[(2\Omega + \omega)t - 2\epsilon - \alpha] - \\ - \tfrac{1}{2}wu \cos\delta(1 + \cos\theta)\cos^2 L \sin[(2\Omega - \omega)t - 2\epsilon - \alpha] + \\ + \tfrac{1}{4}u^2 \sin^2\theta \cos^2 L \cos 2(\Omega t - \epsilon) - \\ - \tfrac{1}{8}u^2(1 - \cos\theta)^2 \cos^2 L \cos[2(\Omega + \omega)t - 2\epsilon] - \\ - \tfrac{1}{8}u^2(1 + \cos\theta)^2 \cos^2 L \cos[2(\Omega - \omega)t - 2\epsilon]\}\,, \qquad (9)\end{aligned}$$

where the test body P is defined by: L latitude, ϵ longitude; $\alpha = 318°$ a right ascension, $\delta = 48°$ a declination; $\theta = 23\overset{\circ}{.}5$ is the tilt of the Earth relative to the Earth orbit (ecliptic); u is the Earth's velocity and w is the solar system's uniform velocity through the Universe ($u \approx 530$ km/sec, $w \approx 200$ km/sec); ω is the angular frequency and Ω is the Earth's rotation frequency ($\omega \ll \Omega$); α_2 is a parameter which depends on the motion through Universal rest-frame ($|\alpha_2| < 3 \times 10^{-2}$).

The tides are affected not only by the variation of G but also by the variation of the Earth's radius, and by the deformation of the Earth. Hence, to the required approximation, Equation (9) becomes, after some simple calculations

$$\Delta G/G = \frac{1}{1.18}\,\alpha_2(3 \times 10^{-8}) \cos^2 L \cos 2(\Omega t - \epsilon - 318°) . \tag{10}$$

Now, since (cf. Nordtvedt and Will, 1972)

$$\Delta g/g = 1.18\,\Delta G/G ,$$

where g is the gravity, it follows that

$$\Delta g/g = \alpha_2(3 \times 10^{-8}) \cos^2 L \cos 2(\Omega t - \epsilon - 318°) ; \tag{12}$$

i.e., as the Earth rotates the anisotropy in G produces "Earth-tides". In Equation (12) the value $\Delta g/g$ has a period around 12 hr and varies with latitude according to $\cos^2 L$. This is completely analogous to the tides produced by the Moon and the Sun (Equations (7) or (8)).

5. Spherical Variation in Earth's Gravitation

The effect considered here is not the same as in the Newtonian theory. It produces a spherical contraction and expansion of the Earth every year. Such periodic pulsations can be accounted according to Nordtvedt and Will (1972). Hence, we obtain, after some, but straightforward, calculations (we shall use the language and notation of the PPN formalism) that

$$\Delta G/G \approx (\tfrac{2}{3}\alpha_2 + \alpha_3 - \alpha_1) wu \cos\beta \sin(\omega t - \lambda) , \tag{13}$$

where α_1, α_2, α_3 are the parametrized Post-Newtonian parameters; u is the Earth's orbital velocity; w is the solar system's uniform velocity through the Universe; ω is the angular frequency; β, λ some constants ($\beta \approx 60°$, $\lambda \approx 346°$).

Equation (13) predicts a sinusoidal variation in the value of G with a period of sidereal year independent of the latitude, but it has no counterpart in Newtonian tidal theory (Equations (7), (8)). Substituting in Equation (13) the numerical values

$$u \approx 30\ \text{km/sec},\ w \approx 200\ \text{km/sec},\ \beta \approx 60°,\ \lambda \approx 346°$$

we obtain that

$$\Delta G/G \approx (\tfrac{2}{3}\alpha_2 + \alpha_3 - \alpha_1)(3 \times 10^{-8}) \sin(\omega t - 346°) . \tag{14}$$

Furthermore, according to Sabbata and Rizzati (1977), we may conclude that the frequency of the earthquakes with focus either near the surface or in the depth (magnitude 5.5 to 7) has a sinusoidal behaviour whose period is a year, taking a maximum about the middle of June (the Earth is at aphelion), and a minimum about the middle of December (the Earth is at perihelion). Also this behaviour

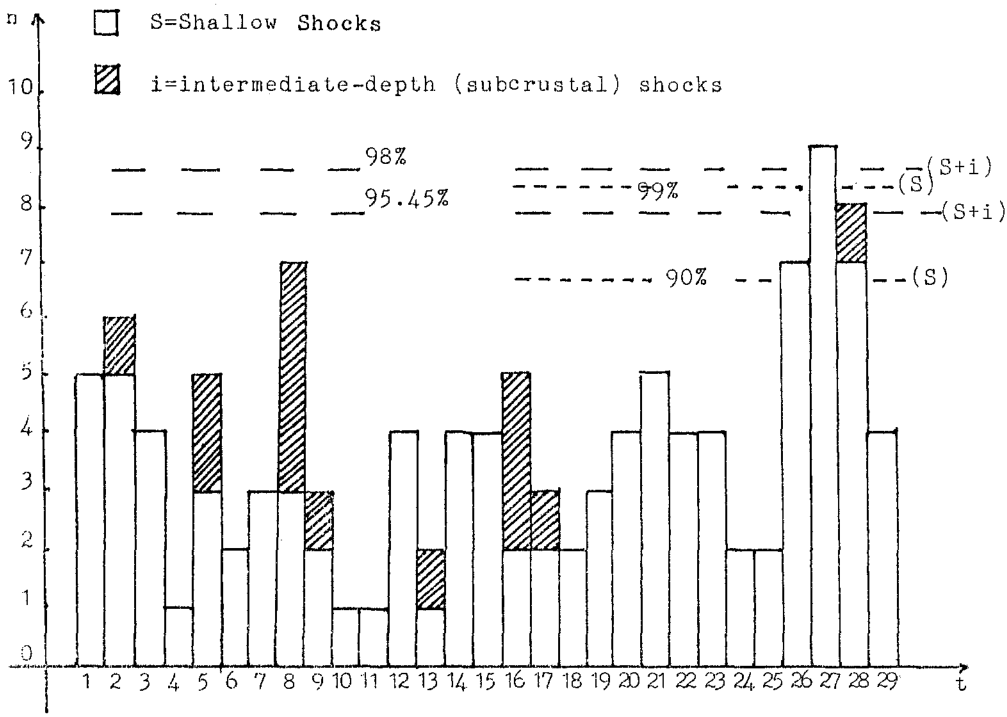

Fig. 1. Distribution of the number (n) of the earthquakes as a function of the Moon age (t).

is independant of the latitude and the hemisphere. Comparing the above with Equation (13) in fact one sees a sinusoidal variation of G with a period of a sidereal year.

6. Investigation of Tidal Triggering of Earthquakes

We consider main earthquakes of surface-wave magnitude $M_s \geqslant 6.0$–7.4 which occurred in the Aegean and surrounding regions (latitude = 34–42° N, longitude = 19–29° E) from 1908 to 1991 inclusive. As data sources have been used the earthquake catalog of Makropoulos *et al.* (1989) for the time interval 1908–1986 and the Bulletin of the Seismological Institute of the National Observatory of Athens, Greece, for the time interval 1987–1991. The earthquake sample examined is complete for $M_s \geqslant 6.0$ and is consisted of 100 shallow (focal depth $h < 75$ km) and 14 intermediate depth ($h = 75$–200 km) earthquake events.

As a first approach of investigating tidal triggering of earthquakes we have examined the frequency distribution of the Moon day, d, corresponding to the origin times of the 114 seismic events considered (Figure 1). Assuming normal distribution for the number of events reported per Moon day and computing confidence levels as $\alpha \cdot \sigma + m$, where σ = standard deviation, m = mean of d respectively and α = parameter, we may conclude that the peaks at $d = 27$ and $d = 28$ are significant at the 98% and 95.45% levels, respectively. When only shallow earthquakes are considered, the peak at $d = 27$ is significant at the 99% level, while the peaks at $d = 26$ and $d = 28$ are significant at the 90% level. Smoothing out the frequency distribution of d, the result does not change.

Previous results indicate that an earthquake triggering effect from Moon gravitational forces may occur at the 26th–28th Moon days. However, the earthquake size, as expressed by surface-wave magnitude, M_S, does not seem to depend on the lunar and solar tidal potential function, U_{TIDAL}, computed from Equation (7) at the timers and locations of the earthquakes (Figure 2).

The search for an earthquake-tide correlation is further conducted by using Equations (7), (12) and computing U_{TIDAL}, $\Delta G/G$ at the times and locations of the earthquakes. From Equation (4a) we see that

$$U_{\mathrm{TIDAL}} > 0, \quad \text{when} \quad \begin{array}{l} \gamma \sim 0° \text{ or } 180° \rightarrow \cos^2\gamma \sim 1 \\ \Gamma \sim 0° \text{ or } 180° \rightarrow \cos^2\Gamma - 1 \end{array} \tag{i}$$

$$U_{\mathrm{TIDAL}} < 0, \quad \text{when} \quad \begin{array}{l} \gamma \sim 90° \text{ or } 270° \rightarrow \cos^2\gamma \sim 0 \\ \Gamma \sim 90° \text{ or } 270° \rightarrow \cos^2\Gamma \sim 0\,. \end{array} \tag{ii}$$

Therefore,

$$(U_{\mathrm{TIDAL}})_{\max} = \frac{1}{2}\frac{GM_LR^2}{d^3}\left(3\cos^2\gamma + \frac{15}{11}\cos^2\Gamma - \frac{16}{11}\right)_{\max} = \frac{16}{11}\frac{GM_LR^2}{d^3}\,,$$

$$(U_{\mathrm{TIDAL}})_{\min} = -\frac{8}{11}\frac{GM_LR^2}{d^3}\,,$$

$$U_{\mathrm{TIDAL}} = 0, \quad \text{when} \quad 3\cos^2\gamma + \frac{15}{11}\cos^2\Gamma - \frac{16}{11} = 0$$

$$\left(\text{e.g.} \quad \cos\gamma = \pm\frac{\sqrt{3}}{3},\ \cos\Gamma = \pm\frac{\sqrt{3}}{3}\right) \text{(Dionysiou } et\ al.\text{, 1993).}$$

Figure 2 shows U_{TIDAL} as a function of the time of occurrence of the earthquake events analyzed. The main feature is that although the highest absolute values of U_{TIDAL} appear in its positive field, a percentage of 64% of the earthquakes occurred when U_{TIDAL} was negative.

Moreover, Figure 3, which represents $\Delta g/g$ equation (12) as a function of the earthquake origin time on a 24-hr basis, indicates that 78% of the earthquakes took place between 00.00 and 18.30 hr. Simultaneously, $\Delta g/g$ is negative.

Table I shows the calculated coordinates of the sublunar and subsolar points and the values U_{TIDAL}, $\Delta g/g$, where

AFT Latitude of the test point (appropriate position).

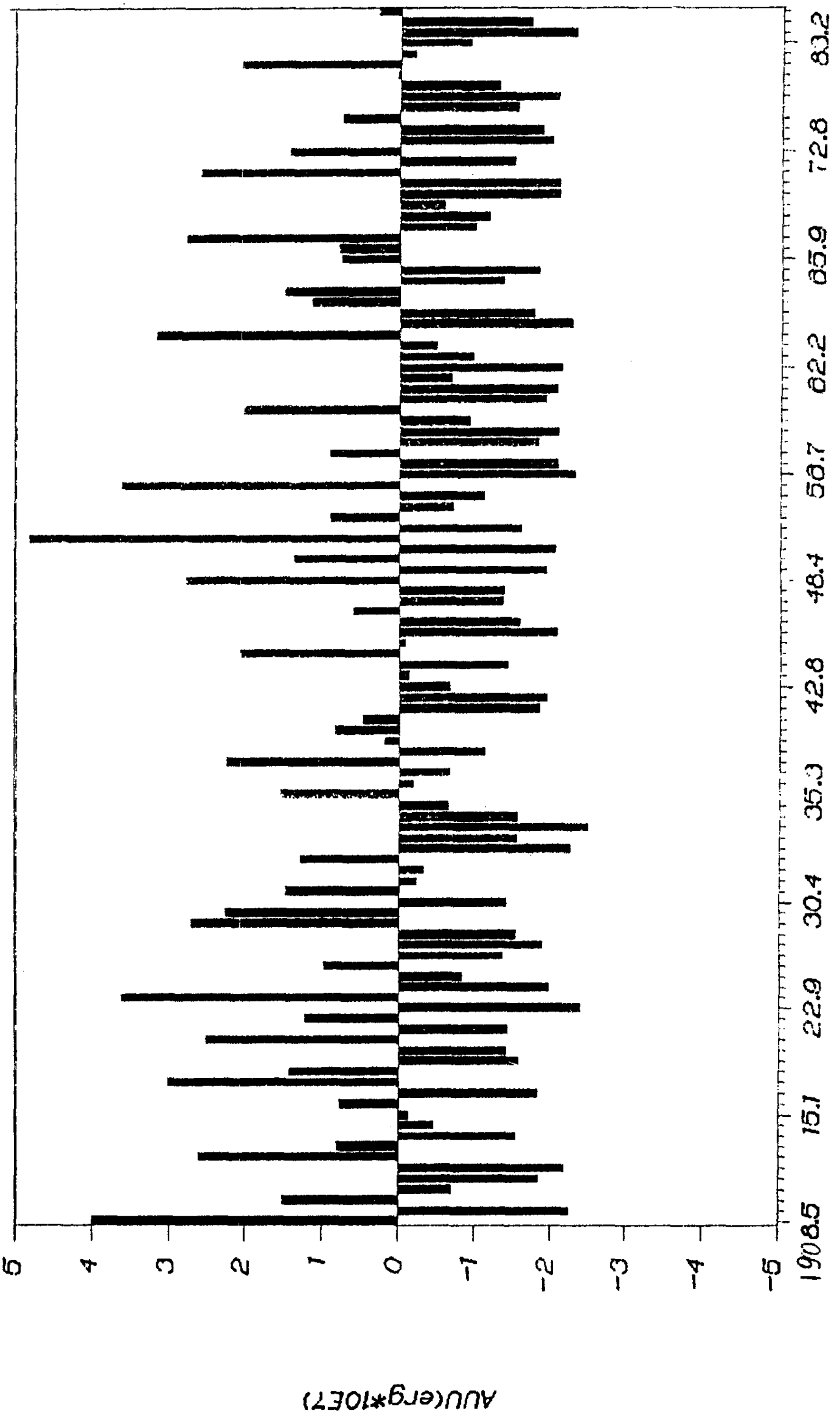

Fig. 2. The potential function U_{TIDAL} as a function of the time (years).

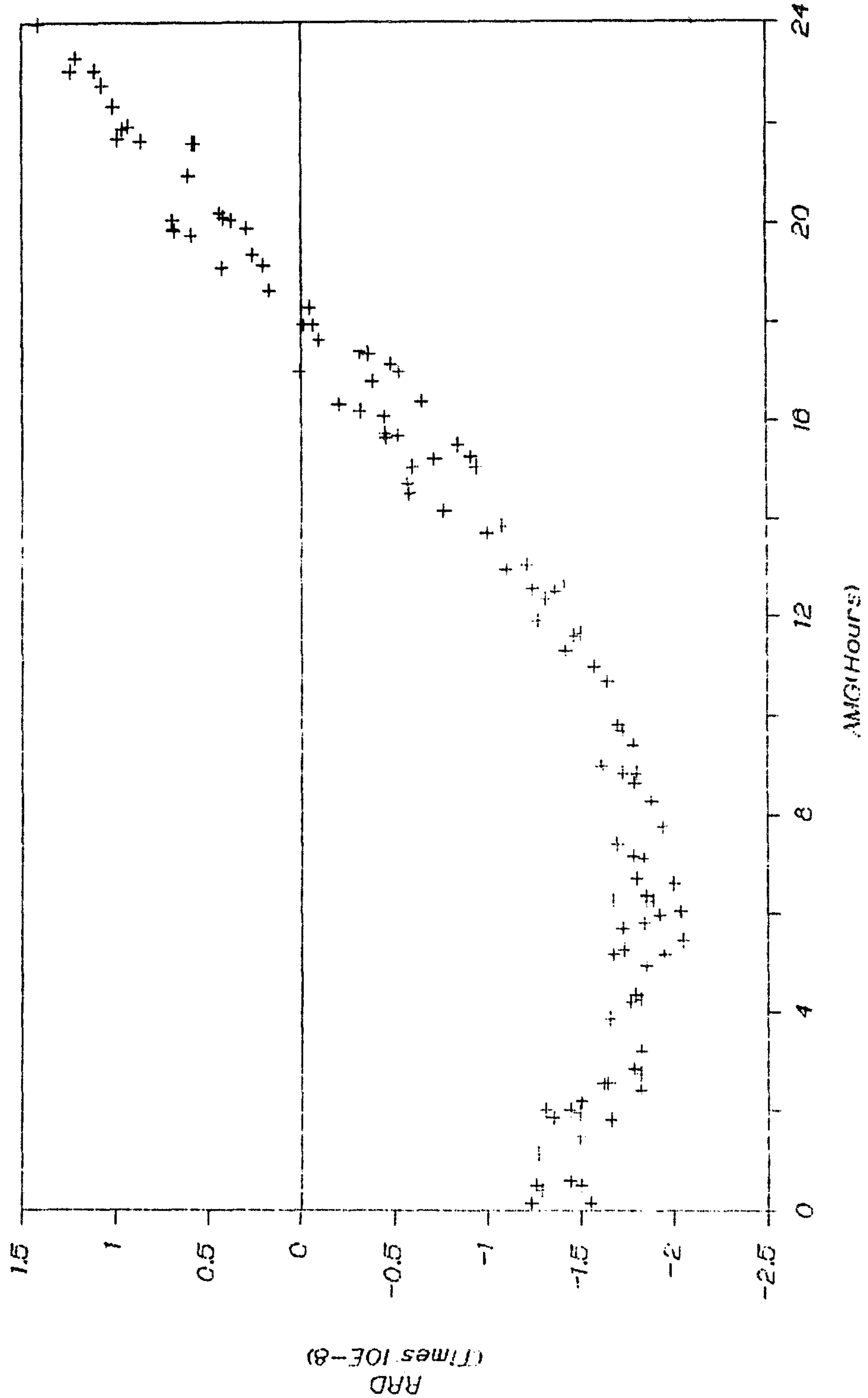

Fig. 3. The $\Delta g/g$ as a function of the earthquake origin time on a 24-hr basis.

TABLE I

No #	AFT (degr)	AFL (degr)	AFS (degr)	ALT (degr)	AAL (hr)	AAS (hr)	ATO (hr)	AMG (hr)	ALL (degr)	ALS (degr)	AUU #	RL (degr)	RS (degr)	RRD #
1	35.50	−21.75	19.20	24.00	17.30	3.55	15.65	12.50	163.26	9.51	4.01	−187.26	−393.51	−0.136E−07
2	38.00	−23.65	−20.45	26.00	17.85	20.03	7.90	4.95	−75.80	−107.50	−2.24	48.30	81.00	−0.185E−07
3	38.25	−3.35	21.70	22.20	13.30	4.40	16.50	6.25	142.01	275.51	1.51	−164.21	−297.71	−0.185E−07
4	35.70	25.05	19.40	24.00	5.55	3.60	9.85	5.15	141.96	171.21	−0.69	−165.96	−195.21	−0.195E−97
5	34.40	−9.80	12.30	27.00	23.25	10.00	21.95	16.20	224.17	62.92	−1.84	−251.17	−449.92	−0.321E−08
6	40.90	−14.75	19.40	20.75	14.55	3.60	9.80	21.60	253.64	57.89	−2.18	−274.39	−438.64	0.571E−08
7	36.50	27.45	5.40	26.50	6.00	0.85	12.80	15.75	338.90	56.15	2.61	−365.40	−442.65	−0.451E−08
8	38.10	1.60	−19.35	20.50	0.50	20.40	7.15	16.40	246.42	47.92	0.81	−366.92	−68.42	−0.651E−08
9	40.60	28.40	16.00	27.20	6.00	9.20	21.15	1.50	249.81	201.81	−1.53	−277.01	−229.01	−0.149E−07
10	40.60	26.95	15.70	27.10	7.50	9.30	21.25	9.40	347.64	320.64	4.09	−374.74	−347.74	−0.150E−07
11	40.10	−15.25	4.00	26.80	14.15	11.35	23.45	23.50	132.97	174.97	2.41	−519.77	−561.77	0.126E−07
12	38.20	−3.05	−9.00	23.50	12.05	16.40	1.65	6.35	−60.49	−80.74	−0.45	36.99	57.24	−0.185E−07
13	38.80	−9.00	−21.00	20.60	0.80	16.15	4.25	14.65	273.60	43.35	−2.28	−294.20	−63.95	−0.101E−07
14	38.50	27.95	−18.60	20.60	5.50	20.60	8.35	1.15	60.05	−166.45	−0.11	−80.65	145.85	−0.127E−07
15	39.10	−1.75	22.35	21.40	23.30	4.80	16.80	17.35	163.46	80.96	0.77	−184.86	−462.36	−0.361E−08
16	38.50	25.95	16.60	20.50	6.90	9.10	21.00	15.05	77.87	44.87	−1.82	−458.37	−425.37	−0.940E−08
17	38.50	17.50	15.70	20.50	9.00	9.30	21.20	2.05	213.83	209.33	−1.99	−234.33	−229.83	−0.142E−07
18	39.00	−27.45	12.95	20.00	17.10	9.85	21.80	6.70	171.28	280.03	3.01	−191.28	−399.03	−0.180E−07
19	40.31	−7.90	12.65	25.29	12.35	9.90	21.90	23.05	129.95	166.70	1.43	−515.24	−551.99	0.111E−07
20	36.22	−16.95	21.45	27.26	14.15	7.65	19.55	20.05	22.57	120.07	−1.58	−409.83	−407.33	0.690E−08
21	36.70	−22.05	−9.65	21.00	17.40	22.45	10.20	1.95	−78.67	−154.42	−1.40	57.67	133.42	−0.149E−07
22	39.41	−10.95	−19.05	26.09	13.20	15.50	3.75	21.90	187.65	153.15	2.52	−213.74	−179.24	0.960E−08
23	40.26	19.35	−20.80	19.44	4.95	16.10	4.35	8.85	124.11	−43.14	−1.42	−143.55	23.70	−0.172E−07
24	34.85	1.25	15.45	27.07	0.25	9.35	21.25	8.30	79.84	303.34	−0.59	−466.91	−330.41	−0.188E−07
25	35.31	7.25	14.85	27.80	1.50	9.50	21.40	0.15	300.76	180.76	1.23	−328.56	−208.56	−0.155E−07
26	36.64	11.65	−15.20	20.32	2.60	14.60	2.85	4.35	69.10	110.82	2.40	89.50	90.56	0.179E−07
27	39.84	−12.90	−22.30	23.60	15.20	16.70	4.90	20.95	160.61	138.11	3.63	−184.21	−161.71	0.611E−08
28	36.75	−22.40	23.35	26.98	19.25	6.30	18.20	19.75	281.31	115.56	−1.98	−308.29	−502.54	0.591E−06
29	36.76	18.95	9.20	23.16	4.55	10.55	22.50	11.65	84.48	354.48	−0.82	−467.64	−377.64	−0.150E−07
30	36.72	22.30	23.15	22.85	8.45	6.65	18.55	8.30	276.34	303.34	0.99	−299.19	−326.19	−0.188E−07
31	38.01	21.65	3.90	27.92	9.00	0.60	12.55	0.50	60.77	186.77	−1.36	−88.69	−214.69	−0.150E−07
32	38.08	21.75	12.00	23.12	4.50	1.95	14.00	20.20	86.33	124.58	−1.90	−469.45	−507.70	0.436E−08
33	35.96	9.50	−13.20	24.71	11.20	21.80	9.55	18.65	255.77	96.77	−1.53	−280.48	−121.48	0.170E−08

34	39.86	−27.55	−10.00	22.75	18.90	22.40	10.15	18.30	144.00	91.50	2.71	−166.75	−114.25	−0.494E−09
35	39.70	9.10	3.90	23.34	1.55	0.60	12.50	12.55	353.02	7.27	2.26	−376.36	−390.61	−0.124E−07
36	37.80	−27.30	10.25	23.17	17.45	1.65	13.65	20.10	245.33	122.33	−1.40	−268.50	−505.50	0.418E−08
37	40.28	−24.80	−19.75	19.64	16.25	15.70	3.95	2.00	−154.42	−146.17	1.48	134.78	126.53	−0.131E−07
38	41.50	−8.95	−5.50	22.48	13.30	23.15	10.90	0.30	−31.49	−179.24	0.86	9.01	156.76	−0.111E−07
39	41.44	−15.80	−5.10	22.61	14.25	23.20	10.95	1.85	−21.67	−155.92	−0.23	−0.94	133.31	−0.135E−07
40	40.39	17.85	−1.00	23.81	9.40	12.15	0.30	19.35	154.55	113.30	−0.32	−178.36	−137.11	−0.257E−06
42	36.76	9.05	12.30	27.17	0.85	20.00	14.05	5.95	287.49	0.24	1.29	−314.66	−27.41	−0.192E−07
43	40.76	−27.70	17.70	23.67	17.05	3.15	15.20	19.15	260.29	108.79	−2.25	−283.96	−492.46	0.200E−08
44	36.47	−26.50	−16.70	25.41	17.00	14.90	3.15	13.70	−1.69	29.81	−1.56	−23.72	−55.22	−0.100E−07
45	40.76	−25.65	−22.75	27.53	18.35	18.95	6.85	14.70	48.60	39.60	−2.48	−76.13	−67.13	−0.571E−08
46	40.69	−25.55	−22.75	27.54	18.45	18.95	6.85	16.35	71.92	64.42	−1.55	−99.46	−91.96	−0.205E−08
47	36.07	−22.30	−9.30	24.83	15.05	22.50	10.25	2.85	−29.13	−140.88	−0.64	4.30	116.05	−0.178E−07
48	36.08	6.30	−1.20	27.30	10.45	23.80	11.65	8.65	148.11	−52.14	1.54	−175.41	24.84	−0.179E−07
49	38.50	10.60	20.75	23.66	1.15	7.90	19.80	0.40	285.77	184.52	−0.20	−309.43	−208.18	−0.129E−07
50	38.78	−17.45	0.55	26.73	19.10	11.90	0.00	0.60	−277.48	−169.48	−0.66	250.75	142.75	−0.144E−07
52	39.73	4.50	−7.80	22.46	0.90	22.75	10.55	3.85	202.66	−125.09	−1.13	−225.12	102.63	−0.165E−07
53	37.15	10.75	20.45	28.14	2.30	3.95	16.00	19.85	144.07	119.32	0.18	−532.21	−507.46	0.681E−08
54	38.25	−3.35	21.90	26.46	23.40	7.45	19.35	15.65	174.64	53.89	0.85	−201.10	−440.35	−0.457E−08
55	37.23	−2.00	−23.10	27.99	12.60	17.30	5.40	6.25	−13.99	−84.49	0.48	−14.00	56.50	−0.189E−07
56	40.82	18.30	23.30	27.70	7.75	5.60	17.55	5.70	232.73	264.98	−1.85	−260.43	−292.68	−0.172E−07
57	41.39	−6.00	10.25	20.45	23.25	10.35	22.30	6.25	79.76	273.26	−1.93	−100.21	−293.71	−0.167E−07
58	35.19	13.85	8.50	26.73	3.55	10.65	22.65	9.70	72.40	325.90	−0.67	−459.13	−352.63	−0.172E−07
59	39.27	18.10	−12.90	27.87	5.20	14.10	2.35	2.40	−6.65	−140.15	1.98	−21.22	112.28	−0.167E−07
60	39.55	−11.95	−18.30	28.58	22.00	15.30	3.55	17.00	−21.05	79.45	−0.12	−7.53	−108.03	0.591E−10
61	38.74	15.55	23.40	29.00	9.85	6.20	18.20	4.25	189.17	243.92	−1.42	−218.17	−272.92	−0.182E−07
62	39.46	17.70	−4.90	26.43	4.35	12.75	0.95	2.55	−12.65	−138.65	2.07	−13.78	112.22	−0.164E−07
63	34.43	22.95	8.15	28.61	7.55	10.70	22.70	11.90	46.24	358.99	−0.08	−434.85	−387.60	−0.127E−07
64	34.20	−20.65	21.45	25.65	21.20	7.65	19.55	5.45	57.22	260.47	−2.08	−82.87	−286.12	−0.205E−07
65	40.09	−23.70	22.35	23.96	16.90	4.75	16.75	0.50	5.27	187.52	−1.59	−29.23	−211.48	−0.126E−07
66	35.50	−16.85	9.20	23.37	22.10	10.55	22.50	22.35	342.17	155.42	0.60	−365.54	−538.79	0.101E−07
67	36.71	26.70	−4.90	21.79	6.35	12.75	0.90	19.90	217.57	121.57	−1.36	−239.36	−143.36	0.289E−08
68	35.32	−21.55	−14.85	27.15	21.15	21.50	9.20	12.95	15.53	10.28	−1.38	−42.68	−37.43	−0.110E−07
69	38.73	−4.80	12.00	20.38	13.15	1.95	14.00	10.70	173.69	341.69	2.78	−194.07	−362.07	−0.164E−07
70	38.96	5.20	23.20	20.53	1.15	6.55	18.55	12.35	86.76	5.76	−0.51	−467.29	−386.29	−0.141E−07

71	34.49	−13.55	20.00	24.99	22.60	8.20	20.10	6.05	53.50	269.50	−1.93	−77.99	−293.99	−0.204E−07
72	37.38	−27.65	4.80	23.28	18.05	11.25	23.30	8.85	211.86	313.86	1.37	−235.14	−337.14	−0.180E−07
73	38.71	18.20	20.20	26.27	6.17	8.10	20.00	15.05	74.12	44.87	−2.04	−460.39	−431.14	−0.602E−08
74	34.47	−26.20	−23.35	24.22	18.55	17.60	5.70	23.05	153.95	168.20	4.82	−178.17	−192.42	0.124E−07
75	40.20	20.95	−1.20	27.52	2.65	23.80	11.70	19.10	63.03	105.78	−1.60	−450.55	−133.30	0.424E−08
76	38.24	16.40	16.00	20.80	8.95	9.20	21.15	7.70	298.82	295.07	1.61	−319.62	−315.87	−0.185E−07
77	38.35	7.35	15.45	20.74	10.35	9.35	21.25	3.55	216.90	231.90	−1.95	−237.64	−252.64	−0.164E−07
78	38.13	0.85	15.15	20.74	11.25	9.40	21.35	9.40	292.89	320.64	0.91	−313.63	−341.38	−0.178E−07
79	37.88	0.20	15.15	20.76	11.30	9.40	21.35	12.10	332.75	1.25	2.50	−353.51	−382.01	−0.149E−07
80	38.12	−0.25	15.15	20.84	11.35	9.40	21.35	14.15	2.83	32.08	1.08	−383.67	−412.92	−0.112E−07
81	38.30	11.15	−10.45	20.59	0.90	13.70	1.95	18.65	296.27	104.27	0.63	−316.86	−124.86	−0.105E−08
82	39.23	7.25	14.60	22.28	0.30	2.45	14.50	13.05	49.29	17.04	−0.70	−431.57	−399.32	−0.121E−07
83	39.31	0.75	10.95	23.06	23.25	1.75	13.75	16.80	110.19	72.69	−1.11	−133.25	−455.75	−0.385E−08
84	37.68	23.30	21.45	27.20	4.45	7.65	19.55	7.10	333.29	285.29	3.63	−360.49	−312.49	−0.184E−07
85	36.64	16.10	22.40	25.91	8.05	7.20	19.10	3.20	213.88	226.63	−2.29	−239.79	−252.54	−0.182E−07
86	36.45	16.10	22.40	25.51	8.05	7.20	19.10	3.40	216.89	229.64	−2.35	−242.40	−255.15	−0.183E−07
87	35.85	14.80	18.65	25.86	1.90	8.60	20.50	9.25	58.13	317.63	−0.23	−443.99	−343.49	−0.177E−07
88	36.27	−14.45	−11.50	21.74	14.05	22.15	9.90	7.75	54.32	−67.18	−2.09	−76.06	45.44	−0.194E−07
89	39.34	20.05	−5.10	22.68	4.25	23.20	11.05	12.15	284.75	0.50	0.75	−307.43	−23.18	−0.134E−07
90	39.34	20.05	−5.10	22.66	4.25	23.20	11.05	12.35	287.76	3.51	0.91	−310.42	−26.17	−0.131E−07
91	39.41	20.45	−5.10	22.76	4.70	23.20	11.05	23.60	90.22	172.72	−1.01	−472.98	−195.48	0.112E−07
92	36.44	−4.85	12.65	28.58	22.35	2.05	14.10	19.15	164.29	108.79	1.57	−192.87	−497.37	0.552E−08
93	36.48	−3.70	13.00	28.58	22.55	2.15	14.15	2.40	−89.90	216.10	−1.82	61.32	−244.68	−0.182E−07
94	37.45	−11.75	10.25	20.67	21.10	10.35	22.30	15.25	247.38	48.63	−2.08	−268.05	−429.30	−0.914E−08
95	35.11	14.60	18.45	24.65	8.35	3.35	15.40	6.60	205.02	280.02	−0.91	−229.67	−304.67	−0.200E−07
96	40.95	11.85	8.50	19.63	9.30	10.65	22.60	11.60	13.98	353.73	2.03	−393.61	−373.36	−0.146E−07
97	37.78	15.25	−18.30	20.46	3.65	15.30	3.55	17.15	256.45	81.70	−1.92	−276.91	−102.16	−0.482E−08
98	40.56	17.40	21.00	20.63	4.80	4.15	16.25	5.15	249.21	258.96	−2.06	−269.84	−279.59	−0.167E−07
99	36.82	9.50	20.45	28.40	10.55	3.95	16.00	2.75	123.11	222.11	−0.68	−151.51	−250.51	−0.182E−07
100	40.69	13.00	−1.20	19.59	10.05	23.80	11.65	15.50	257.14	50.89	−2.13	−276.73	−70.48	−0.841E−08
101	37.76	20.10	7.70	20.09	6.65	1.20	13.15	21.60	62.39	144.14	−0.97	−442.48	−524.23	0.583E−08
102	36.20	−15.40	13.95	26.84	21.45	2.30	14.65	11.30	67.96	355.21	−0.49	−94.80	−382.05	−0.142E−07
103	37.80	16.65	9.90	22.88	9.25	10.40	22.40	11.00	2.70	345.45	3.16	−385.58	−368.33	−0.157E−07
104	38.05	22.90	21.30	23.63	5.90	7.70	19.65	2.55	244.60	217.60	−2.26	−268.23	−241.23	−0.162E−07
105	40.30	−4.65	−4.90	28.23	13.55	12.75	0.95	14.50	29.10	41.10	−1.77	−57.33	−69.33	−0.582E−08

106	39.34	20.30	−4.70	23.82	4.30	23.25	11.10	17.95	11.99	87.74	1.15	−395.81	−111.56	−0.664E−09
107	38.38	−8.10	3.90	22.26	23.60	0.60	12.55	9.80	−18.35	326.65	1.50	−3.91	−348.91	−0.170E−07
108	37.75	17.05	5,80	22.00	3.50	0.90	12.85	3.20	188.38	227.38	−1.27	−210.38	−249.38	−0.166E−07
109	35.06	23.20	7.35	24.31	8.40	1.15	13.15	23.95	71.48	180.23	−1.37	−455.79	−564.54	0.141E−07
110	38.37	−2.90	22.75	22.40	13.20	6.95	18.90	3.30	135.14	228.89	0.45	−157.54	−251.29	−0.166E−07
111	40.51	25.45	11.65	26.17	7.10	10.10	22.05	14.15	77.08	32.08	−1.82	−463.25	−418.25	−0.767E−08
112	40.21	−18.05	−23.40	24.82	15.50	17.85	5.90	0.15	−141.74	−176.99	0.76	116.92	152.17	−0.123E−07
113	39.10	22.85	−16.10	21.74	8.75	21.20	8.95	2.00	33.08	−153.67	0.80	−54.82	131.93	−0.144E−07
114	39.25	−27.45	−6.65	24.60	18.00	22.95	10.75	17.95	161.24	86.99	2.76	−185.84	−111.59	−0.176E−09
115	39.60	−23.25	14.90	21.29	20.85	2.50	14.55	7.15	13.04	288.29	−0.99	−34.33	−309.58	−0.178E−07
116	41.41	−18.95	−21.60	20.44	14.00	16.40	4.55	7.40	−30.45	−66.45	−1.18	10.01	46.01	−0.169E−07
117	39.40	−17.00	−11.50	24.94	14.55	22.10	9.85	22.75	271.68	158.43	−0.58	−296.62	−183.37	0.107E−07
118	38.55	24.70	2.75	28.46	8.20	0.40	12.35	1.80	89.32	206.32	−2.10	−117.78	−234.78	−0.166E−07
119	34.43	23.30	23.10	25.04	3.45	5.30	17.35	15.20	77.12	49.37	−2.10	−462.16	−434.41	−0.716E−08
120	38.34	22.15	6.95	22.56	3.00	1.10	13.05	13.85	359.07	27.57	2.59	−381.63	−410.13	−0.108E−07
121	35.15	−21.50	15.80	23.56	19.80	2.70	14.80	21.65	250.64	147.14	−1.51	−274.20	−530.70	0.862E−08
122	37.96	−22.55	3.80	22.38	15.20	11.40	23.45	4.20	186.92	243.92	1.44	−209.30	−266.30	−0.176E−07
123	40.45	−5.05	2.35	26.12	12.05	0.35	12.25	5.25	81.97	257.47	−2.00	−108.09	−283.59	−0.173E−07
124	37.56	−10.05	17.70	20.35	13.25	3.15	15.25	17.00	285.70	77.20	−1.88	−306.05	−457.55	−0.528E−08
125	34.95	7.60	4.60	23.05	10.15	11.30	23.40	23.30	189.21	171.96	0.74	−572.26	−555.01	0.121E−07
126	40.78	−18.45	23.40	23.24	17.90	5.85	17.90	20.05	301.57	122.32	−1.55	−324.81	−505.56	0.377E−08
127	39.29	16.50	22.35	22.91	4.40	7.20	19.15	2.20	254.34	212.34	−2.09	−277.25	−235.25	−0.150E−07
128	39.23	16.50	22.35	22.59	4.40	7.20	19.15	2.60	260.36	218.36	−1.89	−282.95	−240.95	−0.154E−07
129	38.23	−9.00	−9.65	22.97	14.80	22.45	10.25	5.80	18.99	−95.76	−1.30	−41.96	72.79	−0.184E−07
130	38.17	−11.00	−9.30	23.12	14.85	22.50	10.30	20.90	246.11	131.36	−0.93	−269.23	−154.48	0.600E−08
131	38.24	−15.00	−6.65	23.26	21.75	22.95	10.75	2.60	−125.89	−143.89	−1.47	102.63	120.63	−0.161E−07
132	39.22	0.15	−23.40	25.25	12.90	17.80	5.85	21.95	224.40	150.90	0.03	−249.65	−176.15	0.930E−08
133	38.91	−21.60	−23.30	24.92	19.25	18.40	6.35	14.20	20.08	32.83	−2.10	−45.00	−57.75	−0.863E−08
134	39.96	−12.35	−20.65	24.39	15.00	19.95	7.80	17.65	157.48	83.23	2.05	−181.87	−107.62	−0.100E−08
135	38.07	−14.15	−20.85	20.25	22.40	19.90	7.70	12.70	−29.48	8.02	−0.20	9.23	−28.27	−0.141E−07
136	35.02	17.00	−0.80	25.32	3.90	23.85	11.75	21.70	84.14	144.89	−0.92	−469.46	−170.21	0.986E−08
137	38.23	22.50	0.80	20.29	8.00	0.10	12.00	23.85	58.73	177.23	−0.50	−439.02	−557.52	0.108E−07
138	40.14	24.25	16.90	24.74	6.75	9.05	20.95	15.70	89.15	54.65	−2.30	−473.89	−439.39	−0.523E−08
139	37.10	−28.05	3.80	22.19	19.65	11.40	23.45	17.40	318.72	82.47	−1.72	−340.91	−464.66	−0.317E−08
140	37.99	−25.35	−7.00	29.01	19.95	13.10	1.30	9.00	−144.38	−41.63	0.28	115.37	12.62	−0.161E−07

AFL	Latitude of the sublunar point.
AFS	Latitude of the subsolar point.
ALT	Longitude of the test point (appropriate position).
ALL	Longitude of the sublunar point.
ALS	Longitude of the subsolar point.
AAL	Moon's right ascension.
AAS	Sun's right ascension.
ATO	Sidereal time when $MG = 0$
AMG	Mean time of Greenwich (MG).
AUU	Potential function U_{TIDAL}.
RL	= ALT − ALL.
RS	= ALT − ALS.
RRD	$= \Delta g/g$.

In Table I there are 26 dependent events (foreshocks and aftershocks) which have not been considered in our results.

Concluding Remarks

The purpose of this paper was first to explain the methods used to correlate earthquakes with tides, and then to estimate the significance of results. These are then discussed and interpreted for the Greek area. Also, assuming that there is a link between earthquakes and variation of G we search for periodicity in earthquake occurrences.

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