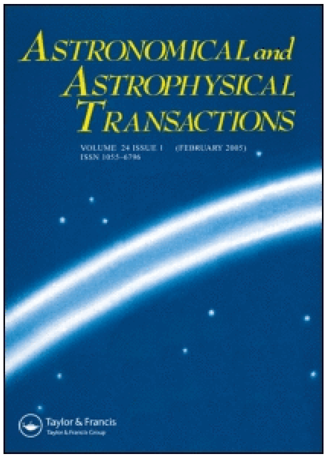

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CONNECTION OF THE EARTH'S ROTATION WITH THE ATMOSPHERIC ANGULAR MOMENTUM AND THE STRONGEST EARTHQUAKES

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Quick changes of the effective atmospheric angular momentum (AAM) functions are compared with the occurence of the strong earthquakes (with a body-wave magnitude $m_b \geq 6.0$) and quick changes of the Earth's rotation parameters (ERP). A strong correlation exists between these changes of the AAM functions and the times of earthquakes. The quick variations of the length-of-day (LOD) (up to 0.2 msec) are induced by the variations of the axial component of the AAM functions and strongly correlate with the times of earthquakes too. Delta-like changes of the equatorial components of the AAM functions correlate with the times of earthquakes and do not correlate with quick variations of polar motion. Common periodicities exist both in the AAM functions and earthquake series.

KEY WORDS Earth's rotation, earthquakes

1 INTRODUCTION

A variety of phenomena perturb the Earth's rotation. The rotation rate and the direction of the rotation axis of Earth are connected with the global properties of the planet, with motions within the oceans and atmosphere, mass redistributions, and other phenomena.

Changes of the angular momentum of the atmosphere are closely related to the Earth's rotation (Barnes *et al.*, 1983; Rosen and Salstein, 1983), on time scales of a few days to a few years (Hide and Dickey, 1991). The AAM functions χ_i ($i = 1, 2, 3$) are the functions of the changes in the atmospheric moment of inertia (the pressure term) and relative angular momentum (the wind term). They are calculated by several meteorological centers and connected with the ERP by the Liouville equation (e.g., Moritz and Mueller, 1987).

The coupling between the atmosphere and the earth's crust is due to mountain torques and surface friction (Salstein, 1994). Applied stresses induced by torques and pressure loading local to the epicenter might be responsible for triggering earthquakes. Such regional effect of the atmosphere on a seismic region is known (Bullen, 1980). At the same time there is a global effect of the atmosphere on seismicity of the Earth (Sytinskij, 1985).

The strongest earthquakes change the Earth's inertia tensor too and are able to shift the pole by amount of 0.01″–0.02″ (O'Connel and Dziewonski, 1976).

The changes of the atmospheric angular momentum and their relation to the Earth's rotation and to the earthquakes are considered in this paper. When the AAM functions are calculated, the local pressure variations are smoothed. So using the AAM functions one can test the hypothesis of relationship of the global atmospheric processes with global seismicity of the Earth.

The purpose of this paper is two-fold: i) to determine the degree of correlation of the quick (delta-like)changes of the AAM functions with the earthquakes and the quick changes of the Earth's rotation parameters; ii) to test the effect of the strongest earthquakes on the rotation of the Earth.

2 THE LENGTH-OF-DAY AND POLAR MOTION DATA

The series of the Earth rotation parameters EOP (IERS)C02 was used in this analysis (IERS, Annual Report, 1991). They raw values of the polar coordinates x, y and of the Universal Time UT1-UTC and their formal errors were used for the period from January, 5, 1984 till February, 21, 1991. These data are tabulated at 5-day intervals for a given 00 hr epoch. The UT1-TAI values were obtained after removing leap seconds from UT1-UTC. Then the contributions of solid-body tides (Yoder *et al.*, 1980) were removed from the UT1-TAI values to form UT1R-TAI series. The 5-day averaged values of $LOD_{\rm ast}$ are estimated by differencing the UT1R-TAI data and dividing by the time interval $\delta t = 5$ days:

$$LOD_{\rm ast} = -\frac{1}{\delta t}((UT1R - TAI)(t) - (UT1R - TAI)(t - \delta t)).$$

3 ATMOSPHERIC DATA

Effective atmospheric angular momentum functions χ_1, χ_2, χ_3 used in this work were obtained by the Japan Meteorological Agency (JMA) (Ozaki *et al.*, 1994). The functions χ_i ($i = 1, 2, 3$) used in this analysis are the sum of the wind term χ_i^w and the pressure term with inverted barometer corrections applied $\chi_i^{p(IB)}$:

$$\chi_i = \chi_i^w + \chi_i^{p(IB)}.$$

The results during 1983/12/1–1986/6/30 are 24-hour (daily) mean values, during 1986/7/1–1991/2/21 they are 12-hour (00 UTC and 12 UTC) values. The 00 UTC values were taken into account to keep homogeneity of the series. The daily mean values χ_1, χ_2, χ_3 were sampled every 5 days at the dates of the ERP data.

4 LIST OF EARTHQUAKES

Only large earthquakes with magnitudes $m_b \geq 6.0$ that occured from January, 5, 1984 till February, 21, 1991 are taken into account in this work (USGS PDE, 1984–1991). The total number of earthquakes is equal to 189.

To decrease the errors of correlation analysis, foreshocks and aftershocks were deleted from the list. An earthquake was identified as a foreshock or aftershock if it occured within a few weeks before or after the main shock and in the region (100–300 km) of the epicentre of this shock. After deletion of foreshocks and aftershocks, 167 earthquakes remain in the list.

5 METHOD OF PROCESSING

To determine the degree of correlation of the continuous equidistant time series (the AAM functions and the ERP data) with the point-like earthquake time series, it is necessary to transform one of them. A common method is the estimation of seismic energy of the earthquakes (Anderson, 1974) or seismic moments (O'Connell and Dzievonski, 1976). Another method was proposed (Zharov *et al.*, 1991) to convert continuous time series to point-like time series. Correlation analysis is reduced in this case to coincidence comparison of two point-like series.

The main idea of this method is to select large peaks of the AAM functions and the ERP data.

The high-frequency oscillations of the χ-functions were calculated using a Gaussian filter with the cut-off period equal to 35 days.

The standard deviation s_0 of the high-pass filtered series was calculated, and any peak exceeding the threshold level $\pm 1.96 s_0$ (95% confidence interval) is used to define the point-like time series. These peaks define the sequence of positive or negative pulses with constant amplitude (+1 or −1).

If one or more earthquakes occure during a 5-day interval, the time series assumes the value equal to unity. A "zero" value indicates the absence of earthquakes in the chosen 5-day interval. The total number of pulses N_e is equal to 150. So, this series is a sequence of positive pulses with an amplitude equal to unity. It is compared with sequences of positive and negative peaks of the AAM functions and of ERP data separately.

To calculate a correlation between two point-like series, the coincidence method is used. The sum of coincident pulses is computed and compared with the number of random (expected) coincidences (Tikhonov, 1970). The expected number n_c of coincidences of the earthquake point-like series with positive or negative peaks of

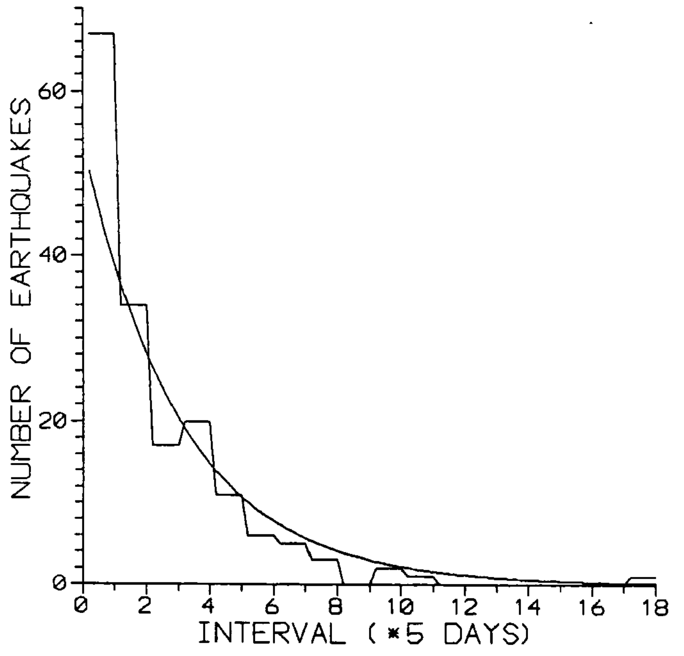

Figure 1 The distribution of the number of earthquakes over intervals between them. The smooth line is the expected probability density of a Poisson process.

the excitation functions is defined by

$$n_c = N_e N_p^{(\pm)} \frac{\delta t}{T},$$

where $N_p^{(\pm)}$ is the number of positive or negative peaks, δt is the sampling interval ($\delta t = 5$ days), T is the length of each series ($T = 2600$ days). Then the probability of k random coincidences of the N_e and N_p pulses is equal to

$$P(k) = e^{-n_c} \frac{n_c^k}{k!}.$$

It is more useful to determine the probability of k random coincidences exceeding k_0:

$$P(k \leq k_0) = 1 - \sum_{l=0}^{k_0-1} e^{-n_c} \frac{n_c^l}{l!}. \tag{1}$$

Then the value $1 - P(k \geq k_0)$ defines a relationship between the two series. The initial hypothesis is that such a relationship exists. The null hypothesis is accepted if $1 - P(k \geq k_0) \geq 0.95$, and it is rejected in the opposite case.

The main condition for application of this method is the independence of the events in each sequence. A dependence between the number of earthquakes and time intervals ν between them is shown in Figure 1. The smooth line is the expected number of earthquakes

$$N_{\text{exp}}(x,\nu) = 167 \cdot xe^{-x\nu},$$

where x is the mean number of events per sampling interval ($x = 167/N = 0.32$). The theoretical distribution is the exponencial distribution with mean value x. The χ^2 test of agreement between the observed and expected distributions of the earthquakes allows us to accept the hypothesis of the independence of the events. The critical χ^2 value for eight degrees of freedom (nine bars were used) at 1% significance level is equal to 2.55. The χ^2 value is found to be 2.12. The number of peaks of the excitation functions is not sufficient for an estimate of their distribution. But one of the conclusions of the monograph of Tikhonov (1970) is that the distribution of the occurence times of excursions of a stochastic process (with zero mean and variance s_0^2) over level C is close to the Poisson distribution if $C \geq 2s_0$.

So, one can consider that the occurence times of earthquakes and peaks of the excitation functions are practically random values.

6 RESULTS AND DISCUSSION

6.1 Connection of the Axial Component χ_3 of the AAM Functions with LOD_{ast} and Earthquakes

The Liouville equation is used to estimate the atmospheric contribution to the LOD:

$$LOD_{\text{atm}} = -\chi_3 LOD_0,$$

where LOD_0 is 86400.0 s.

The high-pass filtered LOD_{ast} and LOD_{atm} series are shown in Figure 2. The horizontal lines are the 95% confidence interval thresholds.

The first natural step in analysis data is comparing plots of series. One can see that they are very similar. For quantitative estimation of a relationship between two series the coefficient of correlation was calculated. It is equal to 0.81. High correlation between the LOD_{ast} and LOD_{atm} series is a well-known result. So it is possible to test the coincidence method and compare it with conventional correlation analysis. The total number of coincident peaks in the point-like LOD_{ast} and LOD_{atm} series is 12. Using (1), one can compute the probability of random coincidence of peaks. The total number of negative and positive peaks is equal to 28 for both series. Then the expected number of random coincidence is $n_c = 1.51$. So, the random coincidence of 12 peaks is absolutely incredible. It means that the proposed method can be used to estimate the correlation coefficient two series. In spite of the large number of the false peaks caused by errors of measurements, the method gives the true result.

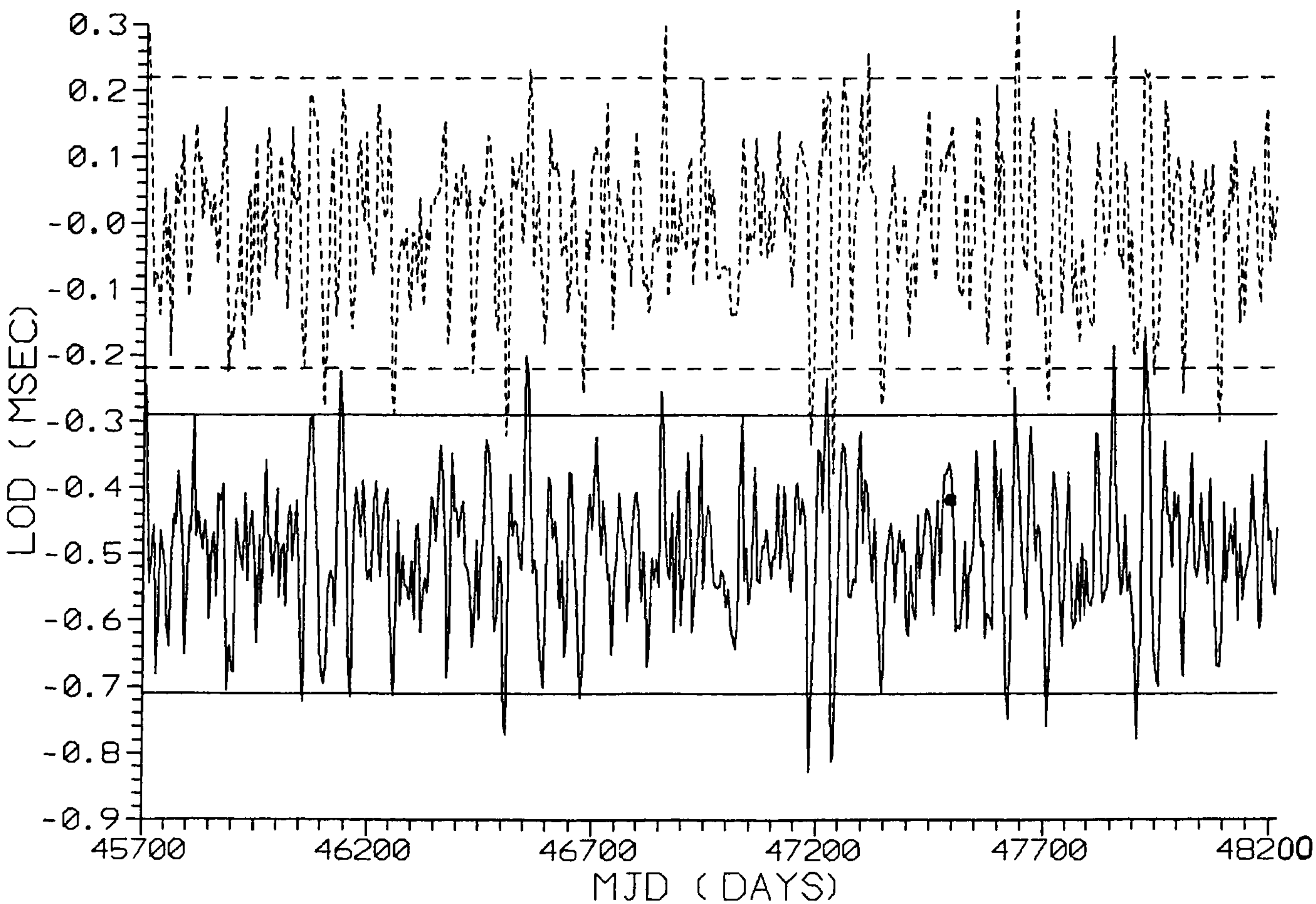

Figure 2 High-pass filtered values of LOD_{ast} (dashed line) and LOD_{atm} (solid line). The horizontal lines are 95% confidence thresholds.

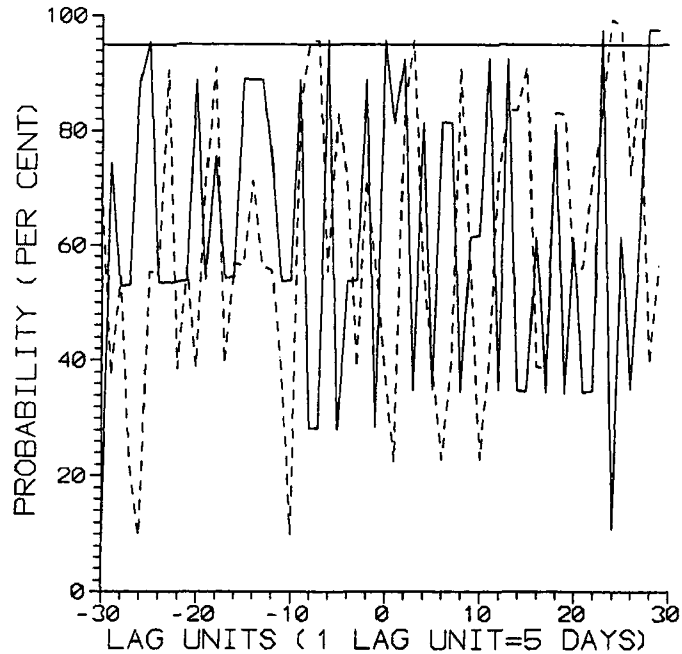

Figure 3 The probability of coincidence of the positive (solid line) and negative (dashed line) peaks of the LOD_{atm} with the earthquake series.

The first result of the analysis is that delta-like changes of the axial component of the AAM functions (up to ± 0.2 msec) and similar changes in the length-of-day are presented. These random variations of LOD were detected earlier (Blinov, Zharov, 1987). Because the dominant contribution to fluctuations in χ_3 originates from the wind term, the reason for them is the change of the relative angular momentum of the atmosphere.

The result of comparison of the point-like LOD_{atm} series with the times of earthquakes are shown in Figure 3. The probabilities $1-P(k \geq k_0)$ were calculated for different lags (1 lag unit = 5 days). At zero lag the probability $1-P(k \geq k_0)$ of coincidences of positive peaks of the LOD_{atm} series with the earthquakes is more than 95% (it correspondes to 7 coincidences of 14 peaks with $N_e = 150$ pulses). So the null hypothesis can be accepted. The positive peaks of the LOD_{ast} series are connected with the earthquakes too.

So, one can say with reasonable confidence that some delta-like changes of the AAM axial component might act to trigger earthquakes. This conclusion can be confirmed by energy estimation. Energy of high-frequency atmospheric excitation is approximately 10^{27} erg. This energy is transferred to the solid Earth and oceans. The mechanism of transferring is the surface friction and mountain torques (Salstein, 1994) that occur at the atmosphere's lower boundary. They act by means of tangential stresses and normal pressure forces on the surface. This additional stress

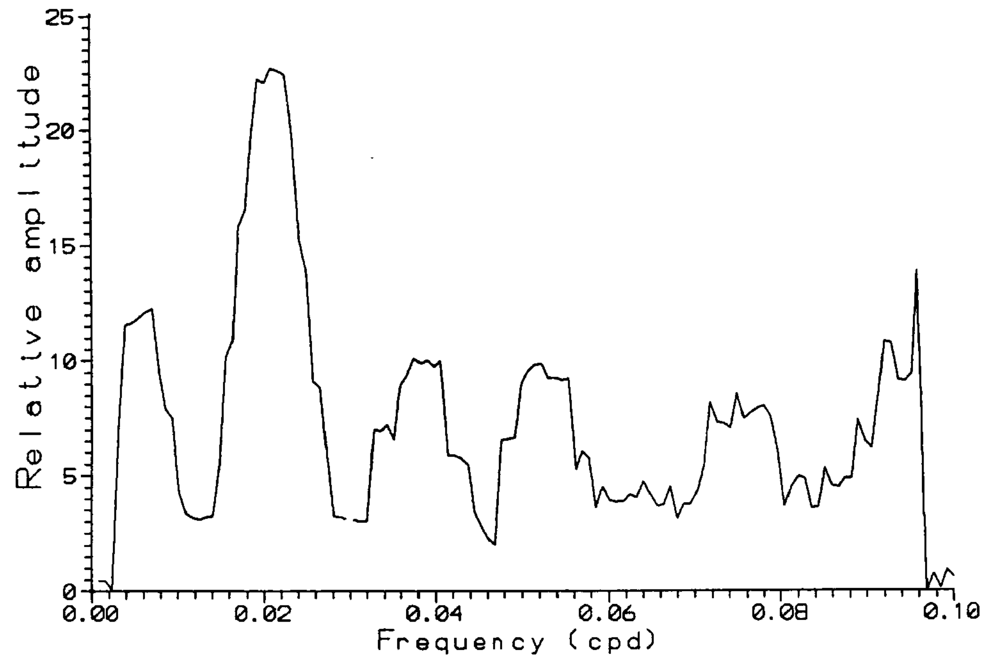

Figure 4 Periodicities in the times of earthquakes.

could trigger earthquakes. Energy released after the strongest earthquakes during the studied period did not exceed 10^{23} erg. So, the effect of one earthquake on the Earth's rotation rate is negligible. On this basis, the positive result of coincidences of the $LOD_{\rm ast}$ series with earthquakes can be interpreted as a common effect of the atmosphere both on the Earth's rotation and on the times of earthquakes.

A further important conclusion can be made from Figure 3. The probabilities $1 - P(k \geq k_0)$ are quasiperiodic functions of the lag between the two series. There is a strong correlation between the peaks of $LOD_{\rm ast}$, $LOD_{\rm atm}$ series and the times of earthquakes at non-zero lags. It can be explained by existence of common harmonics in all series. They can be found using spectral analysis. The main harmonics have periods close to 180, 53, 27, 16 days for coincidences of the peaks of $LOD_{\rm atm}$ and $LOD_{\rm ast}$ series with earthquakes. These periods are close to those determined by spectral analysis (Eubanks *et al.*, 1985) of the AAM and LOD variations. The oscillations of the AAM axial component with these periods are associated with fluctuations in zonal winds (Hide and Dickey, 1991). The energy of these oscillations exceeds the energy of the high-frequency variations of the AAM. So one can expect the appearance of pointed periodicities in times of earthquakes.

The existence of periodicities in the earthquake sequence can be tested by the coincidence method too. The probabilities $1 - P(k \geq k_0)$ of coincidence of earthquakes for different lags were calculated. They are an analog of the autocorrelation function. One can see the peaks with periods 180–220, 40–60, 24–30, 17–19, 13–14, 10–11 days in the spectrum of this function (Figure 4). The harmonics with periods of 180–220, 40–60, 17–19, and 10–11 days are close to ones in the AAM functions. Other two harmonics are close to lunar monthly and fortnightly tides (Kilston and Knopoff, 1983) and confirm tidal triggering of earthquakes (Nikolaev, 1994). The explanation of this result is that although tidal stresses are at least by three orders of magnitude smaller than the tectonic stresses, the tidal stress rates may be comparable to tectonic stress rates. If we suppose that earthquakes result from stress accumulations of the order of 150 bar and the recurrence interval between earthquakes in the same region is 100 years, the average tectonic stress rate would be about 0.004 bars/day. The stress rate caused by rapid variations of the atmospheric pressure can be 0.01–0.02 bars/day (Sytinskij, 1985) and close to tidal stress rates. So, a small external stress can initiate an earthquake if this stress coincides with the direction of the tectonic stress. Apparently both effects can be responsible for triggering earthquakes. Unfortunately the periods of tides are close to periods of some atmospheric harmonics. To resolve them more precisely, it is necessary to increase the length of the earthquake series.

6.2 Connection of the Equatorial Components χ_1, χ_2 of the AAM Functions, Polar Motion, and Earthquakes

The peaks of the χ_1, χ_2 functions were determined using the method described above. The results of comparison of these peaks with the times of earthquakes are not shown because these figures are very similar to Figure 3. The probabilities $1 - P(k \geq k_0)$ are also quasiperiodic functions. At zero lag, there are 8 coincidences of the 15 peaks of the χ_1 function with $N_e = 150$ impulses, that is $1 - P(k \geq k_0) = 0.96$. The same value of $1 - P(k \geq k_0)$ was calculated for the χ_2 excitation function. So, the null hypothesis is verified.

The dominant contribution to fluctuations in χ_1, χ_2 originates from the pressure term. So, the additional stress is caused by the pressure loading.

The effect of the atmospheric excitation and the earthquakes on the polar motion $p(t)$ can be obtained from the equation (Moritz, Mueller, 1987):

$$\frac{i}{\sigma}\frac{dp}{dt} + p = \chi, \tag{2}$$

where $\chi = \chi_1 + i\chi_2$, $p = x - iy$, σ is the complex Chandler wobble frequency.

There are two ways in which the excitation mechanism can be tested. One is to compute a theoretical $p(t)$ for a specified $\chi(t)$; the other one is to deconvolve the observed $p(t)$ to estimate a theoretical $\chi^t(t)$ and to compare this with the observed or model value.

Using the coincidence method one can test the hypothesis of the delta-like changes of polar coordinates caused by the delta-like changes of the AAM functions. The excitation function $\chi = N\delta(t)$ leads to the change of the polar coordinates:

$$p(t) = -i\sigma N e^{i\sigma t},$$

where $N = N_1 + iN_2$, $\delta(t)$ is the delta function. Taking into account that N is equal either to (1,0) or to (0,i), in our case the change of the $p(t)$ is equal either to (0, $-i2\pi/T_c$) or to ($2\pi/T_c$, 0), where T_c is equal to 433 days. The peaks of polar coordinates $p(t)$ were found and compared with the peaks of χ_1, χ_2 excitation functions. Only one coincidence was found. This is strange because the real amplitudes of peaks of the χ_1, χ_2 functions are $0.04''$–$0.05''$. They have to cause the changes of the $p(t)$ with amplitudes 0.6–0.7 mas. The formal uncertainties of the polar coordinates are 2–3 times smaller. So, these changes could be detected.

If an earthquake modifies the inertia tensor according to a step-function, no instantaneous change in the position of the rotation pole occurs and there is only a change in the direction of the pole path. A sufficiently large change in excitation function caused by earthquakes could explain the secular drift in the pole position (Chao, Gross, 1987). To compare the times of the earthquakes with the rapid motions of the pole, the excitation function $\chi^t(t)$ can be determined. As solution of the equation (2) predicts, earthquakes have to cause rapid changes of $\chi^t(t)$. To determine the delta-like changes of the χ_1^t, χ_2^t functions, their time derivatives were found and compared with the times of earthquakes.

At zero lag the probability of coincidences with the times of earthquakes is less than 0.55. This negative result can be explained by small excitation amplitude. Chao and Gross (1987) have found that the effect of all the substantial earthquakes between 1977 and 1985 is two orders of magnitude smaller than that expected from observation. The maximum amplitudes of polar motion excitation are equal to 0.18 and 0.08 mas for Chile (1985, March 3) and Mexico (1985, September 19) earthquakes, respectively. These changes were below the level of detectability because the formal uncertainties of determination of the polar coordinates were equal to 0.7–0.8 mas in 1985–1986.

Another reason for the negative result can be incorrect approximation of the inertia tensor change by a step-function because there are significant pre- and post-seismic deformations.

7 CONCLUSIONS

The variations of the atmospheric angular momentum and their relationship both with the Earth's rotation and the times of earthquakes have been investigated. The atmospheric excitation explaines the high-frequency variations in the LOD. The delta-like changes of the axial component of the AAM induce similar changes in the LOD and are connected with the times of large earthquakes.

Strong correlations are observed not only at zero lag but also at non-zero lags. This can be explained by common harmonics in the series. The periods of the main harmonics are close to the periods of oscillations of the AAM. Periodicities in the times of earthquakes may be connected both with global atmospheric variations and tidal effects.

The delta-like changes of the equatorial components of the AAM are connected with the times of earthquakes too. The earthquakes do not correlate with the rapid variations of the theoretical excitation function because of the small amplitudes of excitation. Another reason for the negative result may be incorrect approximation of the inertia tensor change by a step-function.

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