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A New Method for Identifying Seismicity Periodicities

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A new technique of spectral analysis is proposed to deal with point processes such as earthquakes, volcanic eruptions, etc. The technique is based on the maximum likelihood estimation of spectral parameters of the point process and can be used to analyze catalogs with variable lower levels of complete reporting, as well as catalogs of historical earthquakes. The technique was used in this study to identify periodicities in the 1725–1996 Baikal seismicity and in the worldwide catalog for 1900–1995. The Baikal periodicities are 2.5, 5, 10–11, 18–19, and 35–50 years, the periods for the worldwide catalog being 1.5, 4, 9–10, and 35–40 years. Possible causes of these periodicities are discussed.

INTRODUCTION

A search for periodicities of seismicity has a long history [6], [8], [15], [16], [19], [20], [23], [25], [26]. Periodicities can be caused by external, outer space factors and by internal processes such as periodic oscillations of the Earth's core or hypothetical periodicities of tectonic processes. In his review of the role of outer space factors in geotectonics Kropotkin [6] concluded that tectonic processes could be caused by two factors: (1) the internal evolution of the Earth driven by heat generation due to the decay of radioactive elements and the differentiation of the Earth's silicate shell and (2) external outer space factors, the leading of these being the Sun's electromagnetic radiation and the gravity fields of the Sun and Moon, which have a well-pronounced polyharmonic composition.

Periodicities are inherent in very many natural processes, including the geologic ones. Many investigators attempt to unravel and explain tectonic mechanisms and associated seismicity by appealing to observed quasi-cyclicities and quasi-periodicities. The latter have a vast range of periods, from many million years to a few hours or minutes [1], [2]. Particular interest to periodicities in seismicity was recently evinced in relation to some applied problems that have direct bearing on earthquake prediction and earthquake precursory processes [11], [12], [13], [14], [18].

Since the quantitative evaluation of the effects of these periodic factors is a complicated problem that can hardly be solved in a general form, one has to make use of spectral analysis applied to earthquake catalogs in order to compare its results with the periods of outer space phenomena. A few studies of this kind revealed (to varying degrees of certainty) several periodicities of seismicity. The foremost among these are the 11- and 80–90-year periodicities related to solar activity [16], [19], [26], and also the approximately 19-year seismic periodicity which is probably related to the periods of rotation of the Moon's orbit nodes [19]. The latter was reported for the Baikal seismicity [8]. Also reported was a 5.5-year periodicity [20] and several others. This list of seismic periodicities can be considered neither exhaustive nor sufficiently reliable, because spectral analysis, as applied to earthquake catalogs, is a specific statistical problem that cannot be reduced to the conventional spectral analysis of continuous processes. This paper is concerned with a statistical spectral analysis of seismicity based on earthquake sequences assumed to be a Poisson process with a time-dependent rate. The technique proposed here is applied to search for periodicities in the Baikal seismicity and in the worldwide NEIC catalog.

SPECIFIC CHARACTER OF THE SPECTRAL ANALYSIS OF SEISMICITY

The first distinction to be made is that between periodic and cyclic processes. The latter consist of several phases that alternate in a definite order, the phases having indefinite (shorter or longer) durations. In contrast to cyclic variations, periodic fluctuations can be envisaged as consisting of a sum of harmonics with specified frequencies, amplitudes, and phases. Stochastic narrow-band processes are often classified as periodic processes, an example being a harmonic with a slowly varying amplitude and phase. This study is concerned with periodicities in seismicity.

The seismicity of an area is described by its earthquake catalog. However, catalogs are not homogeneous in time. An instrumental catalog reflects the evolution of an observation seismograph network, such networks being constantly and significantly improved during recent decades. This affected (generally diminished) the lowest completely reported magnitude, involving other catalog parameters as well. An analysis of periodicities of several tens of years requires a catalog whose observation time would be a few times as long. One is thus forced to have recourse to catalogs of so-called "historical" earthquakes, which are inferred from written sources on structural damage and other non-instrumental evidence. The reliability of identifying these earthquakes and the accuracy of determining their parameters are naturally worse than those of instrumentally recorded events. The lowest magnitude of complete reporting for a historical catalog usually decreases as time goes on. Accordingly, the reliability of event identification and the mean rate of earthquake occurrence increase. This seems to be due to increasing population density in the area, hence to the lower probability of missing relatively smaller earthquakes, though other causes may contribute as well.

Spectral analysis has thus to be based on a mixed earthquake catalog (of historical plus instrumental events) involving a time-varying lower magnitude of complete reporting. Moreover, this lower magnitude may sometimes vary nonmonotonically. For example, it went up appreciably during the two world wars (1914–1918 and 1939–1945), decreasing again after the wars. Obviously, seismograph networks operated less efficiently during war time.

Another specific feature of the problem is that spectral analysis has to be applied to point processes (see, e.g., [7], [21], [27], [28]) rather than to ordinary continuous processes (such as Gaussian ones), for which the conventional technique of spectral analysis was developed [3]. A point process is specified by a sequence of points t_k, the times at which the events of interest occurred (earthquakes in our case). A widely known example of a point process is the Poisson process, which behaves independently over two nonintersecting time intervals. This is a typical process with uncorrelated increments. The probability p_n for n points in a sequence $\{t_k)$ to occur in a time interval (T, T') for the Poisson process is

$$p_n = \frac{e^{-\Delta}(\Delta)^n}{n!}, \quad n = 0, 1, 2, \ldots, \tag{1}$$

where $\Delta = \lambda(T-T')$; the parameter λ, which gives the mean number of events in unit time, being known as the rate of the process. If the rate λ is a function of time, then the probability for an event to occur in an elementary time interval $(t, t+dt)$ is $\lambda(t)dt$, while the probability of nonoccurrence is $1-\lambda(t)dt$. In that case the quantity Δ in (1) need be replaced as follows

$$\Delta = \int_T^{T'} \lambda(t)dt.$$

The Poisson model is obviously unsuitable for aftershocks, because the probability of aftershock occurrence depends on the main shock occurrence time. However, once the aftershocks have been eliminated from a catalog using procedures such as, e.g., those described in [9], [22], that is, when a sequence of main shocks remains, the Poisson model becomes quite acceptable.

Our analysis of periodicities in the point process of earthquake occurrence is based on an analogue of a periodogram, namely the square of the absolute value of the Fourier transform applied to the sample of a random process. We use the likelihood ratio, as an analogue in question for each frequency ω, between two hypotheses H_0 and H_1:

H_0 is a Poisson process with a constant rate λ;

H_1 is a Poisson process with the rate

$$\lambda - a[1 + r\cos(\omega t + \varphi)], \quad r \leq 1, \tag{2}$$

where a gives the time-averaged rate of the seismic process (hereinafter understood as a main shock rate); r, ω, and φ are relative amplitude, frequency, and phase of the periodic component. The form (2) for the rate is assumed to hold over a time interval where the recording of earthquakes can be considered to take place under stationary conditions. Because the observation period may comprise several of such intervals, different values of the a parameter ($a_1, \ldots, a_m$) may be relevant to different intervals. Note that the parameters r, ω, and φ are assumed to be constant throughout the entire observation period.

Assuming the observed process to be a Poisson process, it is easy to write down explicitly (apart from a constant that is independent of the parameters) the log likelihood l for an arbitrary time-dependent rate $\lambda(t)$ [7], [21]:

$$l = -\int_T^{T'} \lambda(t)\,dt + \sum_{j=1}^{n} \ln\lambda(t_j). \tag{3}$$

One can thus write down likelihoods l_0 and l_1 for H_0 and H_1, respectively, at any fixed ω. The likelihood l_0 is a function of the $a_1, \ldots, a_m$, and l_1 is a function of ω, $a_1, \ldots, a_m$, r, φ:

$$l_0 = l_0(a_1, \ldots, a_m);$$

$$l_1 = l_1(\omega, a_1, \ldots, a_m, r, \varphi).$$

The maxima of these likelihoods are:

$$\overline{l_0} = \max_{a_1,\ldots,a_m} l_0(a_1, \ldots, a_m);$$

$$\overline{l_1(\omega)} = \max_{a_1,\ldots,a_m, r, \varphi} l_1(\omega, a_1, \ldots, a_m, r, \varphi).$$

The difference between these maxima $L(\omega)$ is a likelihood ratio for the hypotheses H_1 and H_0

$$L(\omega) = \overline{l_1(\omega)} - \overline{l_0} \tag{4}$$

and is an analogue of an ordinary periodogram. Asymptotically (as the observation time $(T' - T)$ increases) and for small r, the function $L(\omega)$ is equivalent, apart from a constant factor, to the periodogram of a point process represented by the sum of δ-functions placed at the points t_k. These two estimates are different for moderate and small values of $(T'-T)$, as well as for r near unity, $L(\omega)$ being the more efficient estimate of the spectrum. We note that for Gaussian processes a periodogram at frequency ω can be derived asymptotically as a difference between log likelihoods for the following two hypotheses H_1 and H_0:

H_0 - Gaussian white noise with a zero mean;

H_1 - Gaussian white noise with the mean $r\cos(\omega t+\varphi)$, where r and φ are some parameters.

The Gaussian assumption can then be discarded, and least squares estimates be used for r and φ. Therefore we have good reason to treat $L(\omega)$ as the analogue of a periodogram for point processes. Naturally, $L(\omega)$ can be used to estimate the spectrum for any (not necessarily Poisson) point processes, though statistical properties of this estimate for an arbitrary point process are much more difficult to derive.

The conventional method used in the spectral analysis of point processes is to sum the numbers of events in successive time intervals $(0, \delta)$, $(\delta, 2\delta$, $(2\delta, 3\delta)$,... . Where the interval δ is long enough and contains at least 10 events on the average, the transformed process can be treated using conventional spectral techniques, even though this process is not strictly continuous, taking on as it does integer values only. Incidentally, the departure from continuity is not large and is decreasing as δ increases. However, this transformation to an ordinary process makes all periods less than δ lost for analysis. Moreover, since a catalog has a fixed length T, this procedure reduces the number of sample data points (which is equal to T/δ), leading to undesirable statistical effects. The parametric method proposed here for the identification of periodicities in a point process is free from these drawbacks.

IDENTIFICATION OF PERIODICITIES IN A POINT PROCESS USING A PARAMETRIC MODEL

Consider an earthquake catalog with aftershocks eliminated. Let the observation time for the catalog be (T, T'), and the occurrence times of main shocks be $t_1,\ldots, t_n$. Suppose further that the entire observation interval (T, T') can be divided into stationary subintervals (T_1, T_1'), (T_2, T_2'),..., (T_m, T_m'), the rate on each subinterval being

$$\lambda(t) = a_i[1 + r\cos(\omega t + \varphi)]; \quad T_i < t \leq T_i'; \quad i = 1,\ldots,m, \tag{5}$$

where a_i, $r < 1$, φ are unknown parameters to be estimated for each of the analyzed frequencies $\omega_0 < \omega \leq \Omega$; ω_0 and Ω are the lower and upper boundaries of the frequency range of interest; $T_1 = T$; $T_m' = T'$. Two successive intervals (T_i, T'_{i+1}), (T_{i+1}, T'_{i+1}) can be strictly adjacent (so that $T_i' = T_{i+1}$), or can have intervening gaps (so that $T_i' < T_{i+1}$). The parameter a_i in (5) gives the background rate, while the component $a_i r\cos(\omega t+\varphi)$ describes a periodic component of the point process with frequency ω, the associated phase being constant throughout the entire interval (T, T'). The assumption of possibly different a_i in different intervals (T_i, T_i') simulates the situation in which the lower completely reported earthquake size may vary over time, while the frequency and phase of the periodic component, as well as the ratio of the amplitude of that component to the background amplitude r, remain constant throughout the entire observation time.

The use of (3) yields likelihood functions $l_0(a_1,\dots, a_m)$ and $l_1(a_1,\dots, a_m, r, \varphi)$ for the hypotheses H_0 and H_1:

$$l_0(a_1,\dots,a_m) = -2\sum_{i=1}^{m} a_i\Delta_i + \sum_{i=1}^{m} n_i \ln a_i; \tag{6}$$

$$l_1(\omega, a_1,\dots,a_m, r, \varphi) = -\sum_{i=1}^{n} a_i \int_{T_i}^{T'_i} [1 + r\cos(\omega t+\varphi)]dt +$$

$$+\sum_{i=1}^{m} n_i \ln a_i + \sum_{j=1}^{n} \ln[1 + r\cos(\omega t+\varphi)]. \tag{7}$$

The following notation is used in (6) and (7): $\Delta_i = (T'_i - T_i)/2$; n_i being the number of events in (T_i, T_i').

It is easy to find the $\hat{a}_i$ values which maximize (5):

$$\hat{a}_i = \frac{n_i}{2\Delta_i}.$$

The maximum $\overline{l}_0$ thus has the form

$$\overline{l}_0 = -n + \sum_{i=1}^{m} n_i \ln\frac{n_i}{2\Delta_i}. \tag{8}$$

It is also easy to find $\tilde{a}_i$ values for which (7) attains the maximum, even though they are functions of r and φ:

$$\tilde{a}_i = n_i \left\{ \int_{T_i}^{T'_i} [1 + r\cos(\omega t+\varphi)]dt \right\}^{-1}. \tag{9}$$

To find the maximum of $l_1(a_1,\dots, a_m, r, \varphi)$ over r, φ we differentiate (6) with respect to r, φ and, integrating the trigonometric functions, obtain two equations:

$$-\sum_{i=1}^{m} a_i \frac{\sin(\omega\Delta_i)}{\omega} \cos(\omega\tau_i + \varphi) + \sum_{j=1}^{n} \frac{\cos(\omega t_j + \varphi)}{1 + r\cos(\omega t_j + \varphi)} = 0; \tag{10}$$

where $\tau_i = (T'_i = T_i)/2$. Replacing the a_i in (10) and (11) with the expressions for $\tilde{a}_i$ as

$$\sum_{i=1}^{m} a_i \frac{\sin(\omega \Delta_i)}{\omega} \sin(\omega \tau_i + \varphi) - \sum_{j=1}^{n} \frac{\sin(\omega t_j + \varphi)}{1 + r\cos(\omega t_j + \varphi)} = 0 , \tag{11}$$

given by (9), we obtain two nonlinear equations for estimating r and φ. Solution of these equations by a standard numerical technique or simple trial-and-error fitting will yield the maximum likelihood estimates $\tilde{r}$ and $\tilde{\varphi}$. Substitution of these in (9) gives the desired values of the $\tilde{a}_i$.

To sum up, substituting the maximum likelihood estimates $\tilde{a}_1, \ldots, \tilde{a}_m, r, \varphi$ into (7), we get $\overline{l}_1(\omega)$ and using (4) we find $L(\omega)$, the quantity which will be called below the generalized spectrum (or simply spectrum) of the point process under study.

A very important problem in spectral analysis is to estimate the significance of spectral peaks. A rigorous solution of this problem is not yet available. In this paper we propose merely some simplified relations that can be helpful to judge about the significance of spectral peaks.

Suppose the observed times $t_1, \ldots, t_n$ are drawn from a Poisson process with a constant rate λ. According to Wilks' theory [17] (see also [10], p.370), the spectrum $L(\omega)$ at any frequency ω is asymptotically disturbed as $0.5\varkappa_2^2$, as the observation time increases, where $\varkappa_2^2$ is a chi-square random variable with two degrees of freedom, in accordance with the two extra parameters r and φ, the likelihood function $l_1(a_1, \ldots, a_m, r, \varphi)$ involves compared with $l_0(a_1, \ldots, a_m)$. Consequently, under the null hypothesis λ = constant, the asymptotic spectrum $L(\omega)$ has a standard exponential distribution for each ω. Hence one easily finds the confidence boundary $u(1-\varepsilon)$ of level $1-\varepsilon$ for $L(\omega)$:

$$u(1-\varepsilon) = -\ln\varepsilon . \tag{12}$$

There is the probability $1-\varepsilon$ of $L(\omega)$ remaining below $u(1-\varepsilon)$, that is, the observed value of $L(\omega)$ is significant at the level

$$1 - \exp[-L(\omega)] . \tag{13}$$

However, the spectrum $L(\omega)$ (similarly to the periodogram) is of interest not for the value of $L(\omega)$ at some frequency ω, but for the values of $L(\omega)$ maxima, which will not be distributed like $0.5\varkappa_2^2$. To overcome this difficulty, consider the $L(\omega)$ behavior as a function of frequency. Examples of $L(\omega)$ for a simulated and an observed catalog are shown in Figs 1 and 2. The spectrum $L(\omega)$ is seen to be oscillatory, similar to ordinary periodograms, hence it should preferably be smoothed over the frequency, similarly to periodograms. It can be shown in a way like that employed for the periodograms of a continuous process that $L(\omega)$ behaves like the sample of a random process for the Poisson process with constant rate λ, and even for more general processes (including those with random rates [21]), the fluctuations of that sample around a mean having a correlation distance equal to $1/(T'-T)$, where $(T'-T)$ is the length of the observation interval. Therefore, asymptotically, when $(T'-T)$ is long enough, the spectrum $L(\omega)$ can be smoothed with a spectral window $w(\omega)$ of width $\Delta\omega$ containing approximately

$\Delta\omega(T'-T)/2\pi$ uncorrelated values of $L(\omega)$ sampled on the axis of circular frequency at intervals of $2\pi/(T'-T)$. In this procedure, as is usual in ordinary spectral analysis, one has to choose a compromise between the frequency resolution as controlled by window width $\Delta\omega$ and the scatter of the local spectral estimate as controlled by the number of degrees of freedom $\Delta\omega(T'-T)2\pi$ (for more detail see [3] where this issue is discussed for ordinary spectral analysis).

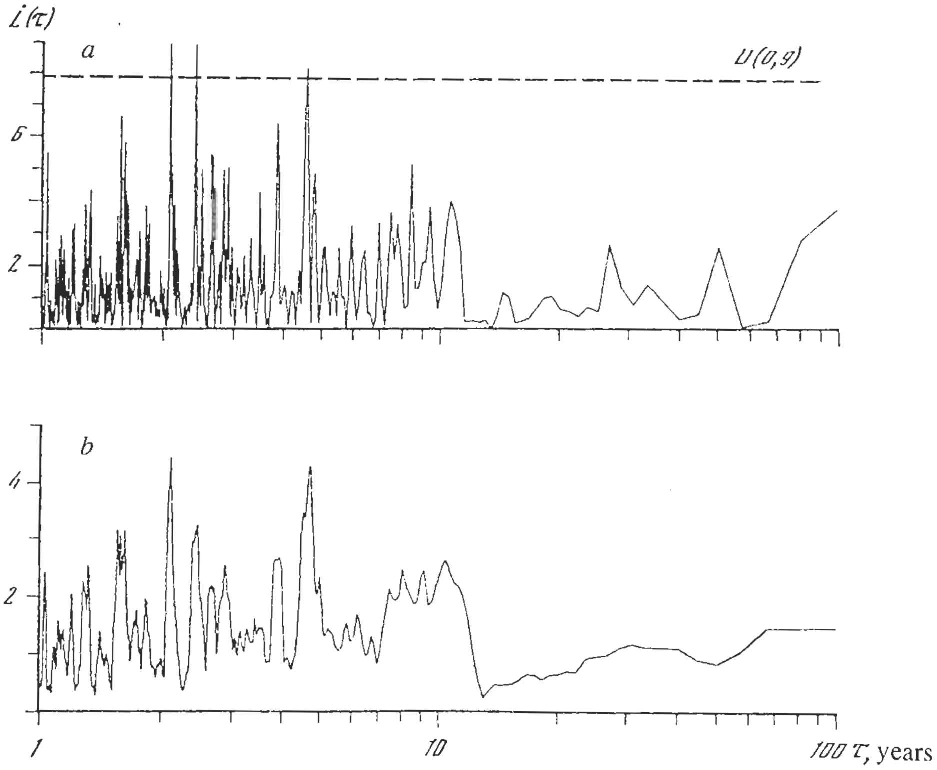

Figure 1 Increments of a log likelihood function for the Baikal region based on historical and instrumental earthquake catalogs for the period of 1725–1996 as a function of period $\tau = \omega/2\pi$. *a* – unsmoothed spectrum; *b* – spectrum smoothed with a window of $\Delta\omega = 0.094$. The dashed line indicates the upper 95% boundary for the highest spectral peak.

Returning to our problem of the significance of $L(\omega)$ spectral peaks, the above considerations suggest that the $L(\omega)$ frequency maximum in the frequency range of interest $\Omega-\omega_0$ has approximately the same distribution as the largest of the $(1/2\pi)(\Omega-\omega_0)(T'-T)$ independent observations of a random variable having a standard exponential probability density. The approximate character of this statement follows from the fact that it refers to discrete values of $L(\omega)$, while in practice we deal with $L(\omega)$ peaks of continuously varying frequency, which are slightly larger.

Denote the integer part of $[(\Omega-\omega_0)2\pi](T'-T)$ by N:

$$N = \text{entier}\left\{\frac{(\Omega-\omega_0)}{2\pi}(T'-T)\right\}$$

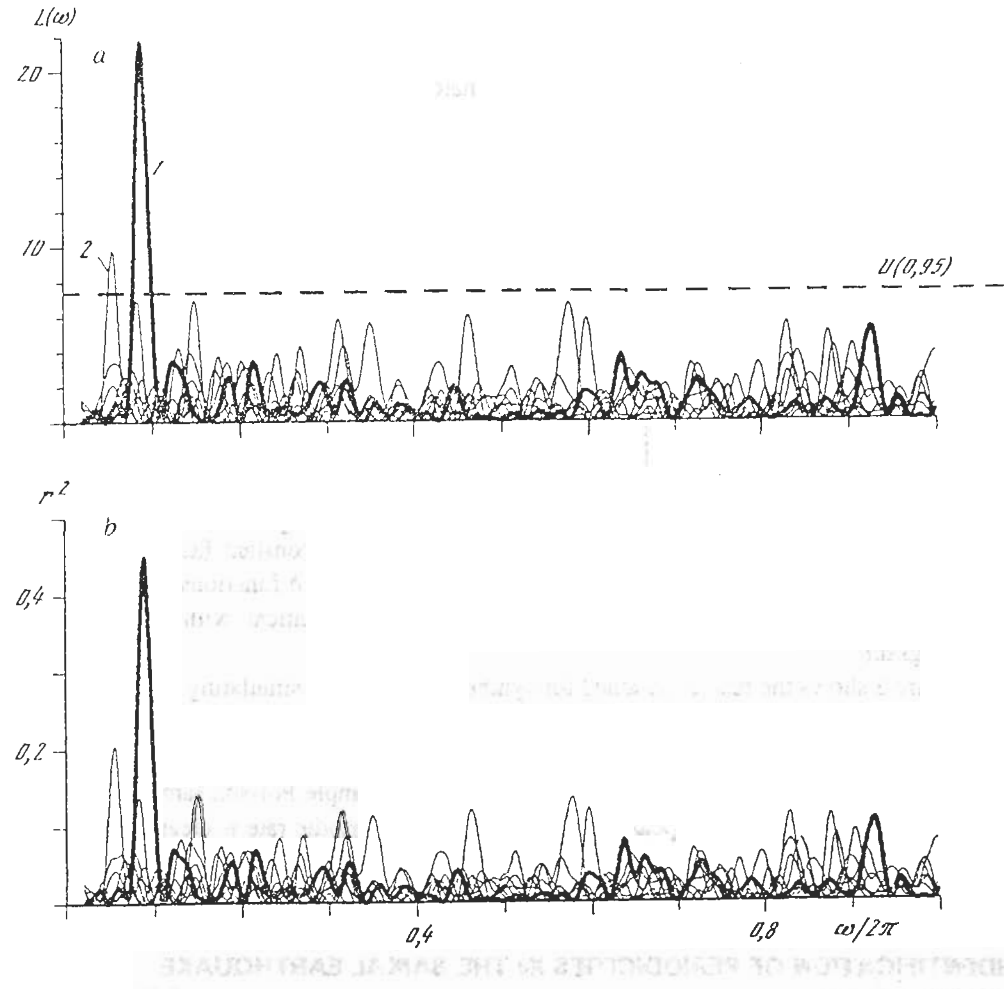

Figure 2 Increments of a log likelihood function for simulated point processes: *1* – 11-year periodicity in a Poisson process, relative amplitude being 0.5; *2* – simple Poisson process, eight samples. *a* – spectra; *b* – estimated amplitudes of harmonics. The dashed line indicates the upper 95% boundary for the highest spectral peak.

Then, in the light of the above approximation, the variable ζ = max $L(\omega)$ has the following distribution function:

$$F(x) = P\{\zeta < x\} \$ (1 - e^{-x})^N .$$

From this one easily finds the upper confidence boundary $U(1-\varepsilon)$ of level $1-\varepsilon$ for the largest $L(\omega)$ peak:

$$U(1 - \varepsilon) = -\ln[1 - (1 - \varepsilon)^{1/N}]. \tag{14}$$

Accordingly, the significance level of the peak max $L(\omega)$ is

$$\{1 - \exp[-\max_{\omega} L(\omega)]\}^N . \tag{15}$$

Relations (14) and (15) provide the approximate significance of $L(\omega)$ peaks.

When r is small and $(T' - T)$ large, one can derive explicit expressions for $\hat{r}(\omega)$ and $L(\omega)$ by expanding the logarithm in the likelihood function (7) in a series in powers of r and retaining the terms of order r^2 alone. The result is

$$\hat{r}^2(\omega) \sim \frac{4}{n^2}\left[\left(\sum_{j=1}^{n}\cos\omega t_j\right)^2 + \left(\sum_{j=1}^{n}\sin\omega t_j\right)^2\right]; \tag{16}$$

$$L(\omega) \sim \frac{1}{n}\left[\left(\sum_{j=1}^{n}\cos\omega t_j\right)^2 + \left(\sum_{j=1}^{n}\sin\omega t_j\right)^2\right]. \tag{17}$$

One can see that these estimates are identical, apart from constant factors, with the periodogram obtained from a sample of a point process with δ-functions at the points $t_1, \ldots, t_n$. It follows that our spectrum $L(\omega)$ is actually identical with the ordinary periodogram.

Figure 2 shows the results obtained for synthetic catalogs by simulating seven samples of a simple Poisson process (*1*) and a sample with a periodic rate (*2*), the period being 11 years. Also indicated in this Figure is the upper confidence boundary $U(1-\varepsilon)$ of level $(1-\varepsilon)$, equal to 0.95. It is seen that all spectral peaks of simple Poisson samples but one are below $U(1-\varepsilon)$, while the peak corresponding to the periodic rate is clearly in excess of $U(1-\varepsilon)$.

IDENTIFICATION OF PERIODICITIES IN THE BAIKAL EARTHQUAKE CATALOG, 1725–1996, AND IN THE WORLDWIDE CATALOG, 1900–1995

Figure 3 shows the M $\geq$ 6.0 seismicity of the Baikal region for the period 1725 to February 1996 based on [4] and a current catalog. The rate shows an overall increase over time until the 20th century. The most likely explanation of this phenomenon is an increasing population density mostly due to the settling of this new territory during the 18–19th centuries. This process was obviously neither uniform in time nor homogeneous over the area. Large earthquakes began to be recorded instrumentally since 1900. However, even the period of instrumental recording contains time intervals with widely differing rates. Examples are the civil war years (1918–1923), when no earthquakes were recorded possibly owing to the civil war conditions and subsequent economic disorganization, as well as the years 1941–1950, during which recording might be hampered by the world war and the postwar rehabilitation of the economy. Taking into account these and other historical and demographic factors, we selected the following six, more or less homogeneous, intervals of earthquake recording, which, in our opinion, were marked by a mean constant rate of earthquake occurrence:

1) 1725–1900: M $\geq$ 6, n = 40;
2) 1900–1917: M $\geq$ 6, n = 18;
3) 1923–1941: M $\geq$ 6, n = 21;
4) 1952–1960: M $\geq$ 6, n = 15;
5) 1960–1987: M $\geq$ 6, n = 25;
6) 1987–1996: M $\geq$ 6, n = 14.

Our catalog thus contained 133 earthquakes of M $\geq$ 6 for the time period of 1725–1996.

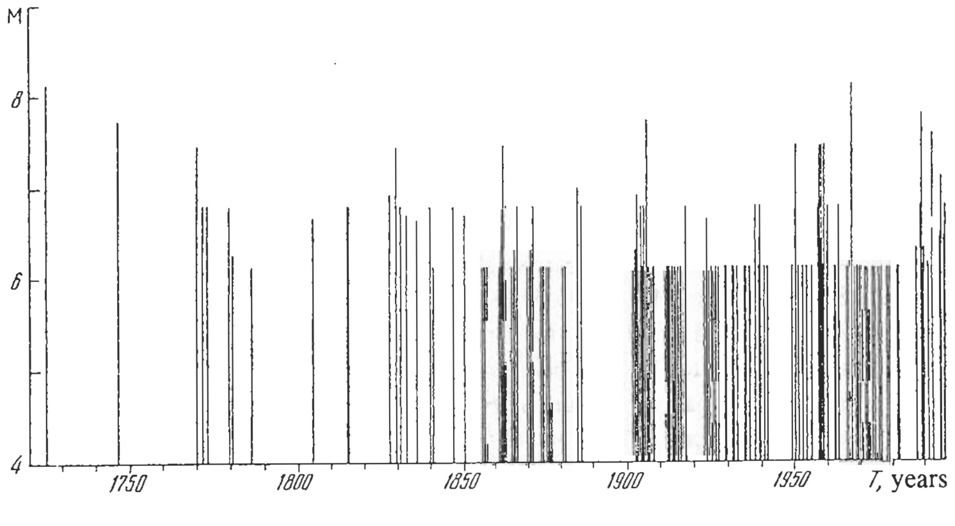

Figure 3 Time behavior of M $\geq$ 6.0 Baikal seismicity for a period of 1725 to 1996.

Each of the selected intervals was assumed to have the form (2) of the rate $\lambda(t)$ with its own mean a_i, the periodicity with frequency ω and phase φ being the same for all intervals. It should be noted that our analytical method does not engender spurious periodicities due to the omission of intervals that are suspicious for deteriorated recording or none at all, or else resulting from the division of an interval into two separate subintervals where actually no changes in recording conditions are present. These operations can at most merely slightly reduce the identification efficiency of the periodicity owing to more nuisance parameters to be estimated and to some slight reduction in the total length of the time interval under study.

A more detailed spectral analysis was done for the instrumentally recorded seismicity of 1952–1996. For one thing, the cutoff magnitude was lowered to M = 4. Secondly, we examined the seismicity for the entire Baikal region as a whole and separately for three subregions (western, central, and northeastern), here denoted as Q_1, Q_2, and Q_3, respectively. Subregion Q_1 is the western part of the Baikal region, bounded on the east by longitude 104°E. Subregion Q_2 is adjacent to Q_1 and is bounded on the east by a straight line approximately passing through the cities of Bratsk and Chita. The remaining, northeastern part of the region is denoted Q_3. The results of our spectral analysis are presented in Fig. 4. We will discuss individual results for the three subregions. Three magnitude ranges were examined for each subregion: $M \geq 5$, $M \geq 4.5$, and $M \geq 4$. This was done to compare almost completely different sets of earthquakes occurring in the same region and examine spectral peaks for stability. In subregion Q_1, three peaks were identified with the periods about 2.6, 6, and 18 years primarily based on the most complete variant of $M \geq 4$. We note that the 10–11-year periodicity was not found, although it was significant at various levels in all of the other spectra; one can just discern a kind of a peak around 8–9 years for relatively higher magnitudes ($M \geq 5.0$, $M \geq 4.5$). Peaks with periods of 2.2, 5, 10–11, and 18 years were identified for the highest-magnitude seismicity ($M \geq 5.0$) in subregion Q_2. The most prominent periodicity of 10–11 years was found in all three variants. This periodicity was also identified in subregion Q_3, in addition to a 2.6-year peak. An analysis of the entire Baikal region for the same observation time, 1952–1996, as well as individual analyses, revealed two most significant peaks with periods of 10–11 and 2.7 years. There was another peak around a period of 40 years for the largest earthquakes ($M \geq 6$), and also a small one with a period of 18 years for the $M \geq 4.0$ seismicity.

We now turn to the results of the entire 1725–1996 catalog whose spectra are displayed in Fig. 1. The total period being about 250 years, the plot of the $L(\omega)$ spectrum in Fig. 1, *a* looks very jagged. Figure 1, *b* shows a smoothed variant of this spectrum with a spectral window being 0.094 wide, that is, equivalent to 3.75 discrete frequency values. One can see that the analysis of the complete catalog gave results that were not very different from those for the 1952–1996 catalog. One can see a 10–11-year period, although the peak is smaller, as well as peaks with periods of 1.8, 2–2.5, 5, 8–9, and 50 years. The most significant are periods of 2.5 and 5 years. The doubling of the 2–2.5-year peak may have been due to some slow variation of the relevant phase over time.

The 10–11-year period, which is very prominent in the instrumental 1952–1996 catalog, might have been related to the known periodicity in solar activity, as reported in

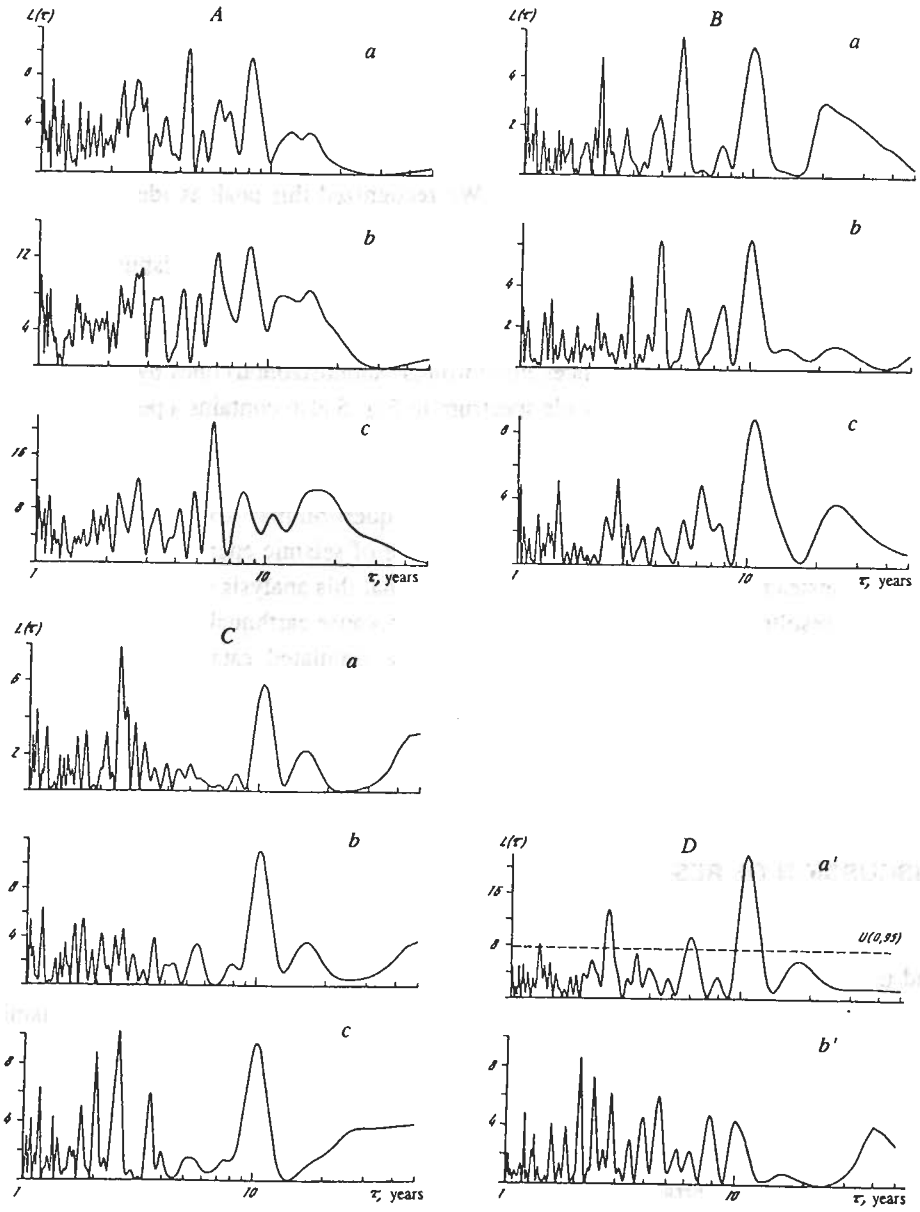

Figure 4 Increments of a log likelihood function for western subregion Q_1 of the Baikal region, 1952–1996: *A* – middle Baikal subregion Q_2, 1952–1996; *B* – northeastern Baikal subregion Q_3, 1952–1996; *C* – entire Baikal region, 1952–1996; *D* – as a function of period $\tau = \omega/2\pi$. The M values: *a* – ≥5.0; *b* – ≥4.5; *c* – ≥4.0; *b'* – ≥6.0.

[16], [26]. The ~2–2.5-year periodicity is fairly strong, its relative amplitude $\tilde{r}(\omega)$ being 0.48. This periodicity had not been identified before, and its further analysis may prove to be very useful both theoretically and practically. Figure 4, *D*, *a'* possibly contains a peak around 18–19 years. This periodicity was first mentioned in [8] and later in [19]; these authors related it to the rotation period of the Moon's nodal line. This implication requires further study. The periodicity seen around 40–50 years in Fig. 4, *D*, *b'* is not very significant, but still there is a peak. We recognized this peak as identified, because the 35–50-year periodicity was clearly identified in the worldwide catalog (Fig. 5) and was mentioned in a review of seismic energy release for the 1910–1990 seismicity [24]. This periodicity had also been identified previously in the Baikal seismicity [11], [12], [13]. A possible cause of the 35–50-year periodicity was suggested in [24]: the conversion of spheroidal (subvertical) disturbances into toroidal (subhorizontal) ones by a plate tectonic mechanism. Note that the worldwide spectrum in Fig. 5 also contains a periodicity around 9–10 years and short-period ones of 1.5–2 and 4 years.

Our spectral analysis of seismicity was based on the times $t_1, \dots, t_n$ of earthquakes with energies above a specified cutoff magnitude. The question may arise as to the possibility of applying spectral analysis directly to a sequence of seismic energies released, say, for one year instead of to times $t_1, \dots, t_n$. The fact is that this analysis would have given very indefinite results from the standpoint of statistics, because earthquake energy estimates are unstable (this can be demonstrated by handling simulated catalogs). We prefer our technique of spectral analysis as applied to point processes, in which earthquake energy can be incorporated into the analysis by a suitable choice of magnitude ranges, as shown above.

DISCUSSION OF RESULTS

The results obtained by the spectral analysis technique proposed here can be interpreted and used as follows.

The periodicities of 2.5, 5, 10–11, 18–19, and 35–50 years identified in the seismicity of the Baikal Rift Zone are not equally significant, the 2.5- and 10–11-year ones being the most significant. It is as yet difficult to say anything definite as to the causes, origins, and mechanisms that are responsible for periodicities or quasi-cyclicities in the release of seismic energy. However, physical experiments on prefailure and failure in solids yielded results that suggest certain possible causes of seismicity fluctuations by relating these, e.g., to some triggering mechanisms in the form of discrete wave movements of various origins. These can be subdivided in size into extraterrestrial, worldwide, regional, and local ones. The last two types can be observed as strain waves that are radiated from regions of high tectonic activity, for instance, from the area of collision between the Hindustan and the Eurasian plate. The origins of extraterrestrial and worldwide triggers

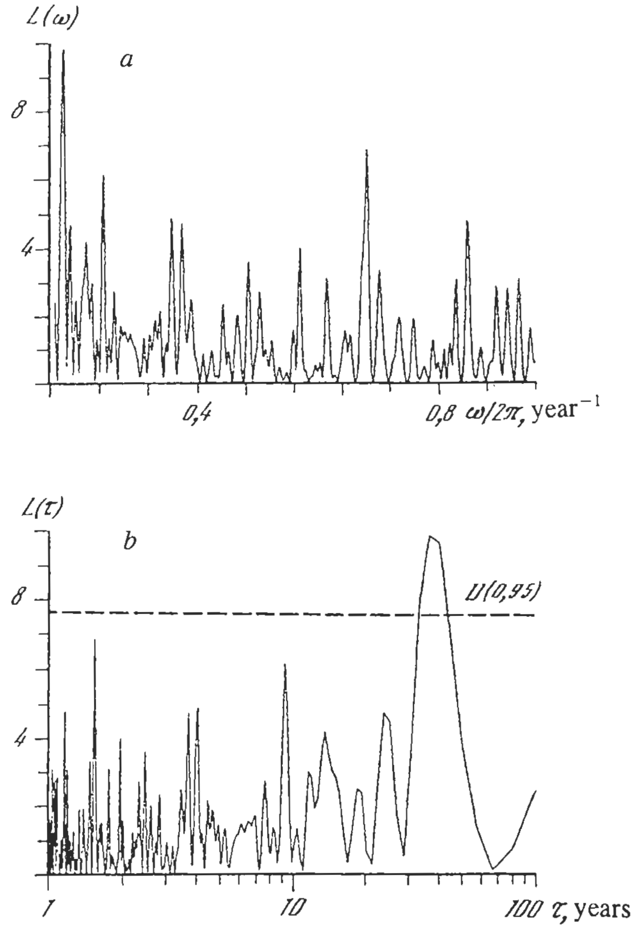

Figure 5 Increments of a log likelihood function for worldwide NEIC catalog, 1900–1995; M ≥ 7.5, depth < 100 km, 296 earthquakes: *a* – plotted against frequency $\omega/2\pi$; *b* – plotted against period $\tau = \omega/2\pi$. The dashed line indicates the upper 95% boundary for the highest spectral peak.

vary greatly and are not yet clear, though judging from the observed harmonics, some of them can be related to the Earth's rotation, the Chandler wobble, the orbital position of the Earth relative to the sun during different months of the year, lunar and solar tides, and possibly to some other outer space-related causes. The action of a triggering mechanism as it affects seismicity can be envisaged as follows. In rock volumes under extreme dynamic instability, very small disturbances due to some oscillators would be sufficient to start avalanche-unstable cracking or rapid slip between the two walls of an earthquake-generating fault (stick-slip model). The authors of [5], for example, give the following explanation of changes in the velocity of the Earth's daily rotation, which can trigger earthquakes. The energy of solar wind coming to the Earth can be transformed to the electromagnetic energy of currents which flow through the ionosphere and are transformed to thermal and mechanical energy. The quasi-periodic effect of the interplanetary space on the Earth is transmitted via magnetospheric–ionospheric–atmospheric disturbances, which have sufficient energy to trigger fracture processes in the crust of seismic regions, and hence outbreaks of seismicity activity. For instance, the energy of magnetic storms is estimated as 3×10^{25} ergs, and that of the solar wind as 6×10^{27} ergs, the values comparable with the energy of large earthquakes. It is significant that seismicity peaks generally occur 3 ± 1 days after magnetic storms, that is, after a time interval that is required to transmit and transform the magnetic-storm energy via the Earth's magnetic field and ionospheric–atmospheric disturbances that do the part of the triggers. The mechanisms of external quasiperiodic disturbances may be very diverse but, even though their origin is as yet unknown, it can be supposed that they exert some regulating effect on seismicity. Therefore the 2.5-, 10–11-, 18–19-, and 35–50-year periodicities identified in the seismicity of the Baikal Rift Zone or other regions can already today be used in earthquake prediction for extrapolating a specified time interval. Such attempts were made in the Baikal region. The results indicate that expected periodic changes in the seismicity "weather" in the region should be taken into account when forecasting for the future few years or tens of years. Obviously, assessments of seismic risk and earthquake hazard for the Baikal region will also be modified in accordance with the observed periodicities in the seismicity of the region.

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