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A New Way for Determining Earthquake Magnitude Based on Electromagnetic Radiation

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Abstract

The article proposes the possibility of determining the magnitude of a future earthquake with high accuracy, based on the frequency data of VLF/LF electromagnetic emissions, as a diagnostic precursor that exists before an earthquake. Such magnitude will contribute to significantly improving the research on various fundamental issues in seismology in the future.

Keywords

Diagnostic Precursor, Electromagnetic Radiation, Magnitude, Accuracy

1. Introduction

Modern ground-based and satellite observations have revealed various anomalous changes in geophysical fields that attend the process of earthquake preparation in the lithosphere, as well as in the atmosphere and ionosphere. They are: changing of intensity of electrotelluric current in focal area; Perturbations of geomagnetic field in forms of irregular pulsations or regular short-period pulsations; Perturbations of atmospheric electric field; Irregular changing of characteristic parameters of the lower ionosphere (plasma frequency, electron content-ration, height of D layer, etc.); Irregular perturbations reaching the upper ionosphere, namely F2-layer, for 2 - 3 days before the earthquake; Increased intensity of electromagnetic emissions in upper ionosphere in several hours or tenths of minutes before earthquake; Lighting before earthquake; Infrared radiation; Total Electron Content

(TEC) anomalies so on. Obviously, all the above-mentioned phenomena are not observed before every earthquake and do not have a specific sequence [1]-[9].

It has been proven that among them there exists a geophysical field (VLF/LF electromagnetic emissions that existed before the earthquakes), the anomalous changes of which accurately describe the geological processes of fault formation in the earthquake focus. Therefore, this field can be considered a diagnostic precursor. In such a case, it is no longer in dispute that it is possible to predict earthquakes based on it [10] [11]. It has been revealed that, based on this precursor field, it is possible to determine with very high accuracy the relationship between incoming earthquake fault length (l) and magnitude (M), which, in modern seismology, despite the very high level of development of this area of science, for the present remains one of the most important problem.

2. Discussion

2.1. Some Information about Diagnostic Precursor of the Earthquakes

As is known, the process of earthquake preparation proceeds in accordance with the well-known avalanche-like unstable geological model of fault formation, which step by step describes the occurrence of cracks of various sizes and the main process of forming the length of the fault in the focus of an impending earthquake. Namely, at the first stage, chaotic crack formation occurs in the earthquake preparation zone, when, as a result of the interaction of cracks, the average density of ruptures reaches a certain critical value in the entire volume or a significant part of it. As a result of the interaction of cracks, an avalanche stage of a given earthquake preparation sets in. It means that the first stage of earthquake preparation goes over to the second stage. The involvement of an increasing number of inhibited cracks in this process leads to the unification of cracks of a higher rank (larger size), which is associated with a rapid and sharp redistribution of the local stress field. An increase in the number and size of cracks, like an avalanche-like process, leads to a sharp increase in the rate of overall deformation, which causes a change in the integral physical characteristics of the medium. The increase in deformation is already accompanied by a drop in stress in the third stage. Due to the heterogeneity of the properties of the medium, the unstable deformation is compressed into a narrow zone, in which several relatively large cracks form. In this case, there is a general drop in average macro stresses over most of the volume. Due to this, the cracks stop developing and partially close. This process can be considered as the so-called main period of the "silence", which immediately begins after the end of the active stage of the avalanche process.

Already then, at the final stage, against the background of increasing tectonic tension, the fault of the earthquake is formed by ripping apart the cofferdam (links between cracks) in the focus of the upcoming earthquake. This process qualitatively is similar to the general process, and therefore it, by short-term and smaller changes in the amplitude of the strain rate, must be preceded. It happens that the

destruction of one of the cofferdams may not be enough to rupture the entire main fault.

Due to this, there can be several such short-term changes in the deformation rate. In this case, as a result, these oscillations must precede large foreshocks, and the final one must be a direct foreshock or the main shock itself [12].

It is widely believed in seismology that "One of the reasons making earthquake prediction so difficult is because we cannot monitor the stress and strain conditions of rocks a few kilometers below the ground surface where earthquakes are initiated" [13]. However, a geophysical field that makes it possible to trace step-by-step the geological process has now been discovered. This field is very low frequency/low frequency (VLF/LF) electromagnetic emissions that existed before the earthquake [10] [11].

It should be noted that research into the interaction between seismic activity and electromagnetic radiation has intensified worldwide since the second half of the last century, as, alongside the theoretical research, it has become possible to conduct high-level laboratory and satellite experiments. Long-term observations have revealed special properties of VLF/LF electromagnetic radiation that manifest themselves both during the preparation of an earthquake and during the earthquake itself.

Networks to collect VLF/LF radio signals associated with seismic activity have been established since the end of the last century in various seismically active regions and countries around the world. One such network, based on the data of which our research was conducted, is the European Network for collecting VLF/LF radio signals (INFREP) [4] [14].

Before an earthquake, as mentioned above, many geophysical fields undergo anomalous changes, which is why all of these fields are referred to in the literature as precursors.

Our group has been studying anomalous changes in various geophysical fields before an earthquake for a long time, and concluded that, for further research in the right direction, it is necessary to classify geophysical fields into triggers, indicators, and precursor according to their generation mechanisms and role in the earthquake preparation process [15].

We think that for the observer, a precursor of an earthquake, or more precisely, a diagnostic precursor of the earthquake, is that geophysical field that is an exact manifestation of the geological stages of the avalanche-unstable model, and on the surface of the Earth, it describes the process of fault formation in the earthquake focus. A study of global scientific research allowed us to develop a model for the generation of electromagnetic radiation recorded before earthquakes, based on electrodynamics and the classical geological model of the avalanche-like process of fault formation. This is the model of electromagnetic radiation of lithospheric origin that exists before and during an earthquake. The seismogenic area is considered to be an oscillatory-distributed system. This model simplifies physical analyses of the nonlinear effects and qualitatively explains the mechanisms that

generate very low frequency electromagnetic waves in the period prior to an earthquake.

Using the VLF/LF electromagnetic radiation that exists in the period preceding the earthquake, the authors obtained formula (1), which, for the first time, analytically links the frequency of the observed electromagnetic radiation and the linear size (length of the fault at the source) of the earthquake:

$$\omega = k\frac{c}{l} \tag{1}$$

where c is the velocity of light, l is the length of the rupture, k is the characteristic coefficient of geological medium and it is approximately equal to 1 [10]. It should be emphasized that the very high accuracy of measuring electromagnetic radiation in the VLF/LF ranges also makes it possible to determine the length of small cracks with high accuracy. For instance, before the L'Aquila catastrophic earthquake (6 April 2009), besides the other electromagnetic anomalies, 41 MHz (ω_1) and about 54 MHz (ω_2) radiation were also recorded [16]. According to our study (formula 1), the corresponding length of the first emitting body (which radiates ω_1 frequency) would be l_1 = 0.007 km, and the corresponding length of the second emitting body (which emitted ω_2 frequency) would be l_2 = 0.006 km. This means that electromagnetic radiation can detect even the slightest changes in the length of the microcracks.

Studies have shown that formula (1) is in good agreement with real earthquake data [11] [17].

To relate magnitude and rupture length l, we used two formulas: for M_S (2) [18] and for M_W (3) [19] for $M \geq 5.0$ earthquakes:

$$\lg l = 0.6M_s - 2.5 \tag{2}$$

$$M_w = 4.38 + 1.49 \times \log l \tag{3}$$

It should be noted that, unlike satellite-based studies, work relying on data from ground-based networks make it possible to record the electromagnetic field at the very moment an earthquake occurs [11] [15] [17] [20].

2.2. Possibility of Increasing the Accuracy of Earthquake Magnitude Measurements Based on Modern Research

Accurate measurement of earthquake magnitude remains one of the main tasks of seismology to this day. The famous scientist C. F. Richter wrote that, "the local magnitude (M_L) requires only a source-receiver distance and a measurement of the peak amplitude of a filtered seismogram" [21]. "Since then, different studies have developed local magnitude formulas that account for the local attenuation properties of a particular region. Despite such widespread use of M_L, the consistency and accuracy of M_L are challenged by large variations in estimates from station to station, influences of radiation pattern and rupture directivity, and spatially variable attenuation structure. In addition, highlights that M_L might not be physically meaningful for small events, as the systematic and random errors in its determination are likely greater than its variability relative to moment magnitude

estimates" [22].

"Conventional magnitude scales, including m_b, M_s, and M_L, encounter saturation issues when the earthquake's rupture dimension exceeds the wavelength of the seismic waves used for magnitude determination. For large earthquakes, rupture dimensions often exceed the wavelengths of seismic waves commonly employed for magnitude estimation" [23].

Almost every famous seismologist in the world has studied and continues to study this issue, but the problem has still not been solved.

Based on the above, we propose a new way for measuring earthquake magnitude that can be used in any region for the entire magnitude spectrum, covering not only small and medium, but also large and very large earthquakes, which is another additional problem in seismology.

Table 1 and Table 2 give data of the fault length, corresponding to the magnitude, measured to tenths of accuracy, as accepted in seismology and of the VLF/LF electromagnetic emissions for earthquakes of magnitudes $M \geq 5$, calculated using formulas (1)-(3), and data of the relevant energies calculated by formulas (4)-(5):

$$\lg_{10} E = 4.8 + 1.5 M_S \tag{4}$$

$$\log_{10} E = 5.24 + 1.44 M_w \tag{5}$$

It should be noted that the lengths of the faults that occurred in the focus of the earthquake are given with an accuracy of even cm, because calculations performed with VLF/LF electromagnetic emissions allow us to measure the existing fault with such accuracy.

Table 1. The diapasons of rupture lengths, EMR frequencies and energies at a fixed magnitude M_S.

M_S	l (km)	Frequency (Hz)	Energy E (joule)
5	3.16228 - 3.62577	94,868 - 82,741	2.00E+12 - 2.81E+12
5.1	3.63078 - 4.16294	82,626 - 72,064	2.82E+12 - 3.97E+12
5.2	4.16869 - 4.77969	71,965 - 62,765	3.98E+12 - 5.60E+12
5.3	4.7863 - 5.48782	62,678 - 54,666	5.62E+12 - 7.92E+12
5.4	5.49541 - 6.30086	54,591 - 47,612	7.94E+12 - 1.12E+13
5.5	6.30957 - 7.23436	47,546 - 41,468	1.12E+13 - 1.58E+13
5.6	7.24436 - 8.30615	41,411 - 36,117	1.58E+13 - 2.23E+13
5.7	8.31764 - 9.53674	36,067 - 31,457	2.24E+13 - 3.15E+13
5.8	9.54993 - 10.9496	31,413 - 27,398	3.16E+13 - 4.45E+13
5.9	10.9648 - 12.5719	27,360 - 23,862	4.47E+13 - 6.29E+13
6	12.5893 - 14.4344	23,829 - 20,783	6.31E+13 - 8.88E+13
6.1	14.4544 - 16.573	20,754 - 18,101	8.91E+13 - 1.25E+14

Continued

6.2	16.5959 - 19.0283	18,076 - 15,766	1.26E+14 - 1.77E+14
6.3	19.0546 - 21.8474	15,744 - 13,731	1.78E+14 - 2.50E+14
6.4	21.8776 - 25.0842	13,712 - 11,959	2.51E+14 - 3.54E+14
6.5	25.1189 - 28.8005	11,943 - 10,416	3.55E+14 - 4.99E+14
6.6	28.8403 - 33.0674	10,402 - 9072	5.01E+14 - 7.06E+14
6.7	33.1131 - 37.9665	9059 - 7901	7.08E+14 - 9.97E+14
6.8	38.0189 - 43.5913	7890 - 6882	1.00E+15 - 1.41E+15
6.9	43.6516 - 50.0495	6872 - 5994	1.41E+15 - 1.99E+15
7	50.1187 - 57.4645	5985 - 5220	2.00E+15 - 2.81E+15
7.1	57.544 - 65.9781	5213 - 4547	2.82E+15 - 3.97E+15
7.2	66.0693 - 75.753	4540 - 3960	3.98E+15 - 5.60E+15
7.3	75.8578 - 86.9761	3954 - 3449	5.62E+15 - 7.92E+15
7.4	87.0964 - 99.8619	3444 - 3004	7.94E+15 - 1.12E+16
7.5	100 - 114.657	3000 - 2616	1.12E+16 - 1.58E+16
7.6	114.815 - 131.644	2612 - 2278	1.58E+16 - 2.23E+16
7.7	131.826 - 151.147	2275 - 1984	2.24E+16 - 3.15E+16
7.8	151.356 - 173.54	1982 - 1728	3.16E+16 - 4.45E+16
7.9	173.78 - 199.251	1726 - 1505	4.47E+16 - 6.29E+16
8	199.526 - 228.77	1503 - 1311	6.31E+16 - 8.88E+16
8.1	229.087 - 262.664	1309 - 1142	8.91E+16 - 1.25E+17
8.2	263.027 - 301.578	1140 - 994	1.26E+17 - 1.77E+17
8.3	301.995 - 346.258	993 - 866	1.78E+17 - 2.50E+17
8.4	346.737 - 397.558	865 - 754	2.51E+17 - 3.54E+17
8.5	398.107 - 456.457	753 - 657	3.55E+17 - 4.99E+17
8.6	457.088 - 524.083	656 - 572	5.01E+17 - 7.06E+17
8.7	524.807 - 601.728	571 - 498	7.08E+17 - 9.97E+17
8.8	602.56 - 690.876	497 - 434	1.00E+18 - 1.41E+18
8.9	691.831 - 793.232	433 - 377	1.41E+18 - 1.99E+18
9	794.328 - 910.752	377 - 329	2.00E+18 - 2.81E+18

Table 2. The diapasons of rupture lengths, EMR frequencies and energies at a fixed magnitude M_w.

M_w	l (km)	Frequency (Hz)	Energy E (joule)
5	2.60679 - 3.03773	115,083 - 98,757	2.75E+12 - 3.82E+12
5.1	3.04243 - 3.54539	98,605 - 84,616	3.84E+12 - 5.33E+12
5.2	3.55087 - 4.13788	84,486 - 72,500	5.35E+12 - 7.42E+12
5.3	4.14428 - 4.82939	72,388 - 62,119	7.45E+12 - 1.03E+13

Continued

5.4	4.83686 - 5.63646	62,023 - 53,224	1.04E+13 - 1.44E+13
5.5	5.64518 - 6.57840	53,142 - 45,603	1.45E+13 - 2.01E+13
5.6	6.58858 - 7.67776	45,533 - 39,073	2.01E+13 - 2.80E+13
5.7	7.68964 - 8.96084	39,013 - 33,479	2.81E+13 - 3.90E+13
5.8	8.97470 - 10.45835	33,427 - 28,685	3.91E+13 - 5.43E+13
5.9	10.4745 - 12.20611	28,640 - 24,577	5.45E+13 - 7.56E+13
6	12.22498 - 14.24595	24,539 - 21,058	7.59E+13 - 1.05E+14
6.1	14.26798 - 16.62667	21,026 - 18,043	1.06E+14 - 1.47E+14
6.2	16.65239 - 19.40526	18,015 - 15,459	1.47E+14 - 2.04E+14
6.3	19.43527 - 22.64819	15,435 - 13,246	2.05E+14 - 2.85E+14
6.4	22.68322 - 26.43307	13,225 - 11,349	2.86E+14 - 3.97E+14
6.5	26.47395 - 30.85047	11,331 - 9724	3.98E+14 - 5.53E+14
6.6	30.89818 - 36.00608	9709 - 8331	5.55E+14 - 7.70E+14
6.7	36.06177 - 42.02328	8319 - 7138	7.73E+14 - 1.07E+15
6.8	42.08827 - 49.04605	7127 - 6116	1.08E+15 - 1.49E+15
6.9	49.1219 - 57.24244	6107 - 5240	1.50E+15 - 2.08E+15
7	57.33097 - 66.80858	5232 - 4490	2.09E+15 - 2.90E+15
7.1	66.9119 - 77.97337	4483 - 3847	2.91E+15 - 4.04E+15
7.2	78.09396 - 91.00398	3841 - 3296	4.06E+15 - 5.63E+15
7.3	91.14473 - 106.2122	3291 - 2824	5.65E+15 - 7.84E+15
7.4	106.3765 - 123.962	2820 - 2420	7.87E+15 - 1.09E+16
7.5	124.1537 - 144.6781	2416 - 2073	1.10E+16 - 1.52E+16
7.6	144.9018 - 168.8561	2070 - 1776	1.53E+16 - 2.12E+16
7.7	169.1173 - 197.0747	1773 - 1522	2.13E+16 - 2.96E+16
7.8	197.3795 - 230.0091	1519 - 1304	2.96E+16 - 4.12E+16
7.9	230.3648 - 268.4473	1302 - 1117	4.13E+16 - 5.74E+16
8	268.8625 - 313.3092	1115 - 957	5.75E+16 - 7.99E+16
8.1	313.7938 - 365.6682	956 - 820	8.02E+16 - 1.11E+17
8.2	366.2338 - 426.7773	819 - 702	1.12E+17 - 1.55E+17
8.3	427.4374 - 498.0987	701 - 602	1.56E+17 - 2.16E+17
8.4	498.8691 - 581.3391	601 - 516	2.17E+17 - 3.01E+17
8.5	582.2382 - 678.4903	515 - 442	3.02E+17 - 4.19E+17
8.6	679.5396 - 791.877	441 - 378	4.21E+17 - 5.84E+17
8.7	793.1017 - 924.2124	378 - 324	5.86E+17 - 8.14E+17
8.8	925.6418 - 1078.663	324 - 278	8.17E+17 - 1.13E+18
8.9	1080.332 - 1258.925	277 - 238	1.14E+18 - 1.58E+18
9	1260.872 - 1469.312	237 - 204	1.58E+18 - 2.20E+18

The fact is that, based on studies of VLF/LF electromagnetic radiation that existed before the earthquake, it was established that to each value of M_s and M_w magnitudes, measured with an accuracy of one tenth, corresponds a certain diapason of rupture length and a certain diapason of earthquake energy.

To overcome this difficulty, we set ourselves the task: with what accuracy should the magnitude of a future earthquake be measured so that one specific magnitude value corresponds to one specific rupture length value and one specific earthquake energy value?

This paper proposes a method to determine the rupture length (*i.e.*, magnitude) of a future earthquake with higher accuracy, and thus provides a completely different way to solve the problem of accurately determining earthquake energy.

In particular, it is proposed to measure the frequency of VLF/LF electromagnetic radiation before an earthquake to within 0.1 Hz, which will make it possible to estimate the earthquake's magnitude to within 0.001. In turn, a specific, unique magnitude value, measured to within 0.001, corresponds to a unique rupture length value, measured to a precision of one meter, and determines a unique, specific value for the earthquake energy.

As an example, the results of calculations for earthquakes $7.4 \le M \le 7.499$ in Table 3 and Table 4 are given. This order of columns in the tables is conditioned by the nature of the set task at hand.

When monitoring the earthquake preparation process, the frequency of the VLF/LF electromagnetic emissions needs to be measured to within 0.1, which ensures the uniqueness of all other parameters.

Table 3 and Table 4 present data on the frequency of electromagnetic radiation (measured with an accuracy of 0.1 Hz), the length of the rupture with an accuracy of one meter, and the energy (measured in joules) for cases of earthquakes of (M_s and M_w) $7.4 \le M \le 7.499$. Magnitude measured with an accuracy of 0.001.

Table 3. The rupture lengths, EMR frequencies and energies at a fixed magnitude M_S.

M_S	Length (km)	Frequency (Hz)	Energy (joule)
7.4	87.096	3444.5	7.943E+15
7.401	87.217	3439.7	7.971E+15
7.402	87.337	3435.0	7.998E+15
7.403	87.458	3430.2	8.026E+15
7.404	87.579	3425.5	8.054E+15
7.405	87.7	3420.7	8.082E+15
7.406	87.821	3416.0	8.110E+15
7.407	87.943	3411.3	8.138E+15
7.408	88.064	3406.6	8.166E+15
7.409	88.186	3401.9	8.194E+15
7.41	88.308	3397.2	8.222E+15
7.411	88.43	3392.5	8.251E+15

Continued

7.412	88.552	3387.8	8.279E+15
7.413	88.675	3383.2	8.308E+15
7.414	88.797	3378.5	8.337E+15
7.415	88.92	3373.8	8.366E+15
7.416	89.043	3369.2	8.395E+15
7.417	89.166	3364.5	8.424E+15
7.418	89.289	3359.9	8.453E+15
7.419	89.413	3355.2	8.482E+15
7.42	89.536	3350.6	8.511E+15
7.421	89.66	3346.0	8.541E+15
7.422	89.784	3341.3	8.570E+15
7.423	89.908	3336.7	8.600E+15
7.424	90.033	3332.1	8.630E+15
7.425	90.157	3327.5	8.660E+15
7.426	90.282	3322.9	8.690E+15
7.427	90.407	3318.3	8.720E+15
7.428	90.532	3313.8	8.750E+15
7.429	90.657	3309.2	8.780E+15
7.43	90.782	3304.6	8.810E+15
7.431	90.908	3300.1	8.841E+15
7.432	91.033	3295.5	8.872E+15
7.433	91.159	3290.9	8.902E+15
7.434	91.285	3286.4	8.933E+15
7.435	91.411	3281.9	8.964E+15
7.436	91.538	3277.3	8.995E+15
7.437	91.664	3272.8	9.026E+15
7.438	91.791	3268.3	9.057E+15
7.439	91.918	3263.8	9.089E+15
7.44	92.045	3259.3	9.120E+15
7.441	92.172	3254.8	9.152E+15
7.442	92.3	3250.3	9.183E+15
7.443	92.427	3245.8	9.215E+15
7.444	92.555	3241.3	9.247E+15
7.445	92.683	3236.8	9.279E+15
7.446	92.811	3232.4	9.311E+15
7.447	92.939	3227.9	9.343E+15
7.448	93.068	3223.5	9.376E+15

Continued

7.449	93.197	3219.0	9.408E+15
7.45	93.325	3214.6	9.441E+15
7.451	93.454	3210.1	9.473E+15
7.452	93.584	3205.7	9.506E+15
7.453	93.713	3201.3	9.539E+15
7.454	93.843	3196.8	9.572E+15
7.455	93.972	3192.4	9.605E+15
7.456	94.102	3188.0	9.638E+15
7.457	94.232	3183.6	9.672E+15
7.458	94.363	3179.2	9.705E+15
7.459	94.493	3174.8	9.739E+15
7.46	94.624	3170.5	9.772E+15
7.461	94.755	3166.1	9.806E+15
7.462	94.886	3161.7	9.840E+15
7.463	95.017	3157.3	9.874E+15
7.464	95.148	3153.0	9.908E+15
7.465	95.28	3148.6	9.943E+15
7.466	95.411	3144.3	9.977E+15
7.467	95.543	3139.9	1.001E+16
7.468	95.675	3135.6	1.005E+16
7.469	95.808	3131.3	1.008E+16
7.47	95.94	3127.0	1.012E+16
7.471	96.073	3122.6	1.015E+16
7.472	96.206	3118.3	1.019E+16
7.473	96.339	3114.0	1.022E+16
7.474	96.472	3109.7	1.026E+16
7.475	96.605	3105.4	1.029E+16
7.476	96.739	3101.1	1.033E+16
7.477	96.872	3096.9	1.036E+16
7.478	97.006	3092.6	1.040E+16
7.479	97.14	3088.3	1.044E+16
7.48	97.275	3084.0	1.047E+16
7.481	97.409	3079.8	1.051E+16
7.482	97.544	3075.5	1.054E+16
7.483	97.679	3071.3	1.058E+16
7.484	97.814	3067.1	1.062E+16
7.485	97.949	3062.8	1.065E+16

Continued

7.486	98.084	3058.6	1.069E+16
7.487	98.22	3054.4	1.073E+16
7.488	98.356	3050.2	1.076E+16
7.489	98.492	3045.9	1.080E+16
7.49	98.628	3041.7	1.084E+16
7.491	98.764	3037.5	1.088E+16
7.492	98.901	3033.3	1.091E+16
7.493	99.038	3029.2	1.095E+16
7.494	99.174	3025.0	1.099E+16
7.495	99.312	3020.8	1.103E+16
7.496	99.449	3016.6	1.107E+16
7.497	99.586	3012.5	1.110E+16
7.498	99.724	3008.3	1.114E+16
7.499	99.862	3004.1	1.118E+16

Table 4. The rupture lengths, EMR frequencies and energies at a fixed magnitude M_w.

M_w	Length (km)	Frequency (Hz)	Energy (joule)
7.4	106.376	2820.2	7.870E+15
7.401	106.541	2815.8	7.897E+15
7.402	106.706	2811.5	7.923E+15
7.403	106.871	2807.1	7.949E+15
7.404	107.036	2802.8	7.976E+15
7.405	107.202	2798.5	8.002E+15
7.406	107.367	2794.1	8.029E+15
7.407	107.533	2789.8	8.055E+15
7.408	107.7	2785.5	8.082E+15
7.409	107.866	2781.2	8.109E+15
7.41	108.033	2776.9	8.136E+15
7.411	108.2	2772.6	8.163E+15
7.412	108.368	2768.4	8.190E+15
7.413	108.535	2764.1	8.217E+15
7.414	108.703	2759.8	8.244E+15
7.415	108.871	2755.6	8.272E+15
7.416	109.04	2751.3	8.299E+15
7.417	109.208	2747.0	8.327E+15
7.418	109.377	2742.8	8.354E+15
7.419	109.546	2738.6	8.382E+15
7.42	109.716	2734.3	8.410E+15

Continued

7.421	109.885	2730.1	8.438E+15
7.422	110.055	2725.9	8.466E+15
7.423	110.225	2721.7	8.494E+15
7.424	110.396	2717.5	8.522E+15
7.425	110.567	2713.3	8.551E+15
7.426	110.738	2709.1	8.579E+15
7.427	110.909	2704.9	8.608E+15
7.428	111.08	2700.7	8.636E+15
7.429	111.252	2696.6	8.665E+15
7.43	111.424	2692.4	8.694E+15
7.431	111.597	2688.3	8.722E+15
7.432	111.769	2684.1	8.751E+15
7.433	111.942	2680.0	8.781E+15
7.434	112.115	2675.8	8.810E+15
7.435	112.289	2671.7	8.839E+15
7.436	112.462	2667.6	8.868E+15
7.437	112.636	2663.4	8.898E+15
7.438	112.81	2659.3	8.927E+15
7.439	112.985	2655.2	8.957E+15
7.44	113.16	2651.1	8.987E+15
7.441	113.335	2647.0	9.017E+15
7.442	113.51	2642.9	9.046E+15
7.443	113.685	2638.9	9.077E+15
7.444	113.861	2634.8	9.107E+15
7.445	114.037	2630.7	9.137E+15
7.446	114.214	2626.7	9.167E+15
7.447	114.39	2622.6	9.198E+15
7.448	114.567	2618.5	9.228E+15
7.449	114.744	2614.5	9.259E+15
7.45	114.922	2610.5	9.290E+15
7.451	115.1	2606.4	9.321E+15
7.452	115.278	2602.4	9.351E+15
7.453	115.456	2598.4	9.383E+15
7.454	115.634	2594.4	9.414E+15
7.455	115.813	2590.4	9.445E+15
7.456	115.992	2586.4	9.476E+15
7.457	116.172	2582.4	9.508E+15
7.458	116.351	2578.4	9.539E+15
7.459	116.531	2574.4	9.571E+15

Continued

7.46	116.712	2570.4	9.603E+15
7.461	116.892	2566.5	9.635E+15
7.462	117.073	2562.5	9.667E+15
7.463	117.254	2558.5	9.699E+15
7.464	117.435	2554.6	9.731E+15
7.465	117.617	2550.7	9.763E+15
7.466	117.799	2546.7	9.796E+15
7.467	117.981	2542.8	9.828E+15
7.468	118.163	2538.9	9.861E+15
7.469	118.346	2534.9	9.894E+15
7.47	118.529	2531.0	9.927E+15
7.471	118.713	2527.1	9.960E+15
7.472	118.896	2523.2	9.993E+15
7.473	119.08	2519.3	1.003E+16
7.474	119.264	2515.4	1.006E+16
7.475	119.449	2511.5	1.009E+16
7.476	119.633	2507.7	1.013E+16
7.477	119.818	2503.8	1.016E+16
7.478	120.004	2499.9	1.019E+16
7.479	120.189	2496.1	1.023E+16
7.48	120.375	2492.2	1.026E+16
7.481	120.561	2488.4	1.030E+16
7.482	120.748	2484.5	1.033E+16
7.483	120.935	2480.7	1.036E+16
7.484	121.122	2476.9	1.040E+16
7.485	121.309	2473.0	1.043E+16
7.486	121.496	2469.2	1.047E+16
7.487	121.684	2465.4	1.050E+16
7.488	121.873	2461.6	1.054E+16
7.489	122.061	2457.8	1.057E+16
7.49	122.25	2454.0	1.061E+16
7.491	122.439	2450.2	1.064E+16
7.492	122.628	2446.4	1.068E+16
7.493	122.818	2442.6	1.071E+16
7.494	123.008	2438.9	1.075E+16
7.495	123.198	2435.1	1.078E+16
7.496	123.389	2431.3	1.082E+16
7.497	123.579	2427.6	1.086E+16
7.498	123.771	2423.8	1.089E+16
7.499	123.962	2420.1	1.093E+16

From Table 3 and Table 4, it is clear that one value of the frequency of electromagnetic radiation corresponds to only one value of the magnitude, length of the rupture, and energy of the earthquake.

We have conducted similar calculations for earthquakes of magnitude $1 \leq M \leq 9$, but due to the large volume of data, we could not include the corresponding tables in the article.

The proposed method will allow for the accurate solution of some fundamental problems of seismology in the future.

As we noted above, in our model, the seismogenic area is considered to be an oscillatory-distributed system, which is characterized by the following features:

1) The segment of earth crust, where the incoming earthquake focus is to be formed from the very starting moment of earthquake preparation, belongs to the system, which suffers specific type oscillations: the process of energy accumulation is in progress in the system. But as a result of foreshocks, the main shock, and aftershocks, the accumulated energy is released. Taking this into account, this system is an oscillatory system [24].

2) In the seismogenic area, the mass, elasticity (mechanical systems), capacity, and inductance (electric systems) elements are uniformly and uninterruptedly spread in the whole volume of the system.

In addition, due to piezoelectric, piezomagnetic, electrochemical, and other effects, every tiny element in the earthquake preparation zone has its capacitance and inductance. Therefore, seismogenic zone can be considered a distributed system simultaneously. The relationship between the arrangement of elements (or groups of elements) plays a significant role in terms of the functioning of the system, since this system is constantly subject to tectonic stress, which changes the physical and chemical properties of the environment.

As a rule, in distributed systems, it is impossible to isolate a single point, since each channel for the passage of energy is considered as a pair of poles (connection points) [24], and therefore, the radiation frequency in the system will change in accordance with changes in the lengths of the combined fractures involved in the process of fault formation. This means that during the processes of closing and opening of cracks of different sizes in the focal zone and their ordering in a certain direction, which ultimately leads to the formation of the main fault, the emitted frequency in the system accurately reflects the change in the smallest distances between the pair of poles (connection points), which is also accurately reflected in the magnitude value.

The need for increased accuracy was clearly demonstrated by the example of an actual earthquake. In particular, in the case of hourly earthquake monitoring, it has become not only possible but also necessary to calculate changes in the length of a fault at the focus with an accuracy of up to a meter in the period preceding an earthquake [11].

As mentioned above, the ultimate formation of the fracture length occurs by the rupture of a cofferdam between major fractures.

The analysis of the Crete (25.05.2016, $M = 5.6$) earthquake convinced us that the final formation of the fault length does indeed occur in accordance with the classical geological model. Before the first destruction of the cofferdams (16:00, 24 May), the length of the fault was 7828 meters. At the moment of the first destruction of the cofferdam, the length of the rupture became 7.5 km. That is, the length of the fault at the focus decreased by 328 m. It happened 16 hours before the earthquake. The process of the first destruction was expressed in the EM radiation in the form of an anomaly. The second destruction of another cofferdam occurred at 22:00 (24 May), which again was recorded by an electromagnetic radiation anomaly. As a result, the length of the rupture became 7.496 km. This time, the length of the fault decreased by 4 m. The earthquake occurred 16 hours and 36 minutes after the first anomaly and 10 hours and 36 minutes after the second, with the fault length decreasing by 21 m.

The above indicates that for a complete consideration of the complex geological process of earthquake preparation and occurrence, it is desirable to measure the fault length with an accuracy of meters by the formula (1).

Research on the Crete earthquake indicates that, on the scale of kilometers, rupture occurring at the earthquake focus is sensitive to the destruction on the scale of meters of cofferdams [11].

Studies also confirm that during the nucleation stage, high-frequency FEMR (Fracture-Induced Electromagnetic Radiation) pulses in the MHz range appear as microcracks form. As the system transitions into the stick-slip phase, the frequency decreases to the kHz range [25] [26]. Since the MHz range in the main corresponds to meter-scale ruptures, we believe they should be influenced by the destruction of centimeter-scale cofferdams.

Based on this view, it is better if the unified magnitude scale is divided into three subscales, depending on the accuracy of measuring the rupture length, where earthquakes are classified by magnitude as follows:

1) $1 \le M_s \le 3.909$; 2) $3.91 \le M_s \le 8.909$ and 3) $8.91 \le M_s \le 9$

Furthermore, it should be noted that, as previously mentioned, electromagnetic radiation in the MHz range is observed even during the period preceding an earthquake [16].

It is possible that, from a geological perspective, determining the length of the rupture in centimeters may not be of great importance; however, it is important for initial monitoring of the length of the rupture at the focus of an earthquake, even in the case of a strong earthquake, as well as for underground engineering applications. Thus, when determining length with such high precision using formulas (1), (2), and (3) for a specific electromagnetic radiation frequency, we obtain a precise and unique value for the magnitude and, consequently, a precise and unique value for the energy of the earthquake, which is of great importance in seismology.

2.3. Advantages and Potential Difficulties of EM Emissions That Existed before Earthquakes

As is known, for decades, theoretical, laboratory, and observational studies have

been conducted on the EM radiation that occurs before an earthquake, which has revealed the advantages of this field compared to other geophysical field anomalies related to earthquakes:

1) Scientists note that electromagnetic radiation before an earthquake, at very large distances from the earthquake's epicenter, can be observed [27]-[30]. For example, at the time of the earthquake in Crete, between the electromagnetic radiation receiver and the epicenter of the earthquake, the distance was approximately 200 km [31].

2) Scientific studies confirm that pre-earthquake electromagnetic emissions are observed considerably long before the earthquake [14] [16] [30] [32] [33].

3) Our theoretical and retrospective material studies have revealed a key and decisive advantage in this field: electromagnetic radiation in the range 23,830 kHz $\geq f \geq$ 0.378 kHz is responsible for earthquakes with magnitude $1 \leq M \leq 9$.

4) Formula (1) is valid for earthquakes of any magnitude and can be applicable in all seismically active countries and regions, because, as it was mentioned above, in a system where earthquakes are being prepared (distributed system), it is impossible to isolate a single point, since each channel for the passage of energy is considered as a pair of poles (connection points) [24]. Therefore, the radiation frequency in the system will change in accordance with changes in the lengths of the combined fractures involved in the process of fault formation. This means that during the processes of closing and opening of cracks of different sizes in the focal zone and their ordering in a certain direction, which ultimately leads to the formation of the main fault, the emitted frequency in the system accurately reflects the change in the smallest distances between the pair of poles (connection points), which is also accurately reflected in the magnitude value.

Thus, the problems associated with the precise measurement of the magnitude of earthquakes of varying strengths, as well as the limitations of the applicability of the magnitude estimation formulas existing only for one region (country), are possible to be solved.

5) Based on the above, it is clear that the high accuracy of measuring the frequency of VLF/LF emissions (0.1 Hz) that existed before an earthquake allows, based on formula (1), to determine with very high (meter or centimeter) accuracy the length of the rupture occurring in the earthquake's focus and, consequently, allows measure the magnitude of an earthquake to within 0.001 for any region. This, in turn, in any region allows us to accurately estimate the energy of earthquakes, which is of crucial importance in modern seismology.

From the above, it is clear that the formula created by famous seismologists for any country or region, which links the length of the fault at the focus of an earthquake to the magnitude of the earthquake, is completely acceptable. It is also worth noting that the characteristic parameters of a future earthquake can be determined with such precision in advance, before it occurs.

6) Calculations for magnitudes Ms and Mw, based on the frequency of VLF/LF emissions that existed before the earthquake, accurately reflect the entire spec-

trum of earthquake magnitudes, from small to medium and large.

7) It is worth emphasizing that the VLF/LF electromagnetic radiation that existed before an earthquake always appears from the moment when the avalanche-like unstable process begins, and therefore, monitoring the frequency of this field and, hence, all other parameters becomes possible precisely from this moment on. This means that the length of the main fault of an incoming earthquake (*i.e.*, magnitude), several tens of days before the earthquake, can be determined.

8) Seismology currently lacks a reliable criterion for distinguishing strong foreshocks from the main shock. This question can be answered with a fairly high degree of accuracy using a theoretical model [10]: if a trend toward decreasing electromagnetic radiation is observed after any tremor, this indicates that fault formation at the earthquake's epicenter has not yet been completed, and the main shock should be expected. The situation is reversed with aftershocks.

9) Due to the determination in advance of fault length and magnitude with high accuracy, it also becomes possible to calculate in advance with high accuracy: the surface rupture length, downdip rupture width, rupture area, maximum and average displacement per event, the average subsurface displacement on the fault plane, seismic moment, and others [19].

10) Although the paper proposes a completely new parameter (VLF/LF electromagnetic radiation that existed before the earthquake) to determine the length of the rupture formed at the earthquake focus, it should be emphasized that this study does not take into account errors in formulas (2)-(5), which may be insignificant, but when monitoring real earthquakes can still appear. Therefore, from our point of view, it is desirable to specify the real errors when using formulas (2)-(5).

3. Conclusions

To obtain specific and unique values of earthquake characteristic magnitudes, the article proposes a completely new parameter, the frequency of the earthquake's prognostic precursor, *i.e.*, the frequency of the VLF/LF electromagnetic emissions that existed before the earthquake, and calculations based on it. This allows us:

1) During the monitoring of the earthquake preparation process, the frequency of VLF/LF electromagnetic radiation has to be measured within 0.1 Hz.

2) Based on the frequency of VLF/LF electromagnetic radiation, the length of the rupture occurring in the earthquake focus in advance, before the onset of an earthquake, has to be precisely determined with high accuracy (km, m, cm).

3) Based on the rupture length, the magnitude of a future earthquake has to be determined to within 0.001.

4) According to the one-thousandth magnitude, the energy of the upcoming earthquake should be measured (in joules).

5) Such precision measuring of these parameters was chosen because, in that case, one concrete, unique value of the fault length corresponds to a concrete, unique value of the magnitude and energy of the earthquake.

6) The magnitude, fault length, and earthquake energy with high precision early detection, it becomes possible to resolve various geophysical and engineering problems in advance, including those related to seismic hazard.

We propose that various international agencies, such as the ISC, NEIC, and GCMT, consider adopting the method we have presented for measuring magnitude with a precision of one-thousandth, which is completely different from existing magnitude measurement methods.

It is based on a high-precision numerical estimate of the rupture length at the earthquake source, which, in turn, is determined from the frequency of electromagnetic emissions in the VLF/LF ranges observed before the earthquake. Measuring the magnitude with a precision of one-thousandth ensures the uniqueness of the earthquake's corresponding energy.

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Author Contributions

M.K. and N.K.-M.: conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, and writing—editing. B.K.: conversion of electromagnetic radiation amplitude data recorded by the INFREP network into frequency values based on the Gaussian normal distribution, data curation. G.R. and V.K.: visualization and writing—review and editing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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