Microwave ultra-refractometry of the atmosphere

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Analysis of data of four-year continuous measurements of the refractive index (RI) at the frequency of 10 GHz shows that the RI fluctuations time behavior can be used for short-term forecast of geo- and tropospheric catastrophes. Mechanisms for formation of seismic centers are proposed. A different possible source of infrasound in the atmosphere is discussed.

Introduction

The refractive index (RI) of electromagnetic waves in the atmosphere depends mostly on meteorological parameters and is, in fact, the integral characteristic of the atmosphere. In 1988 during the mission of the research vessel *Professor Bogorov*, a modified refractometer operating at the frequency of 10 GHz was used to study the dynamic processes in the atmospheric surface layer above the water surface. Variations of the refractive index in space and time were studied in the mode of continuous measurements in the water-air interface. An advantage of this device is its high sensitivity allowing reliable measurements of RI variations of ±0.01% of the mean value as low. Therefore, it proved possible to follow the relief of the sea bottom down to the depth of 5 km and to detect the underwater mountain called Kagoshima V from RI variations in the atmospheric surface layer. Then this device was used under the laboratory conditions for continuous sensing of the atmosphere to study dynamic processes caused by the meteorological conditions.

For more than four years of continuous observations, we have collected voluminous data on intense RI oscillations of different periods. Usually, such oscillations precede (roughly by two or three days) the passage of cyclones or magnitude 5 and higher earthquakes (on the Richter scale). Analysis of the statistical material shows with high reliability that the short-period RI oscillations are related to atmospheric cyclone fronts. The long-period (more than 10^3 s) RI oscillations can be attributed with the same reliability to the precursors of both the atmospheric cyclonic fronts and earthquakes. The passages of cyclones were identified using the space weather maps. The long-period RI oscillations were compared with the NEIC (USA) data.

In Ref. 1 it was shown that the short-term and seasonal motions of both regional and local air masses can be caused by perturbations of the gravitational field due to violation of the equilibrium distribution of mass in the Earth's crust. This violation may be stimulated by tidal forces and, most likely, in the zones of tectonic breaks. As a result, local spots of excessive and missing mass arise thus causing local jumps of the force of gravity. The excess mass in the region of unstable tectonic formations may then become a seismic center with the lifetime determined by mechanoelastic properties of the underlying rocks. Thus, in our opinion, the atmospheric perturbations being a precursor of an oncoming catastrophe arise in the Earth–Moon system due to the disturbed distribution of masses in the Earth's crust. To determine the coordinates of a seismic center or a nucleus of an incipient cyclone, a global observational network is needed.

Measurement system

The basis of a measurement system is a precision refractometer operated at the working frequency of 10 GHz that allows the atmospheric refractive index to be measured with the error no higher than ±0.01%. It employs the method of comparing the data of two generators, one having the frequency related to the frequency of a vacuum resonator and the other one having the frequency related to the frequency of an open atmospheric resonator.

Figure 1 depicts schematically the measurement system with an airway connecting the space between window-frames with a ventilation channel. The space between the window-frames serves as a choke filter for high-frequency oscillations connected with the 3D turbulence in the atmosphere.[4] The airway provides for non-forced flow of atmospheric air through the resonator. To monitor the dynamics of atmospheric parameters, temperature and humidity sensors are installed at different points of the airway near the resonator. This experimental arrangement provides for the overall idea of the process observed.

As temperature sensors, we used KMT-17V termistors, whose resistance was measured with V7-40 digital voltmeters; humidity was measured with E7-8 digital devices connected with lag-free hygrometers made from counter combs evaporated onto a

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glassceramic substrate. Such constructions are used for generation of surface acoustic waves in solid-state bodies.[5]

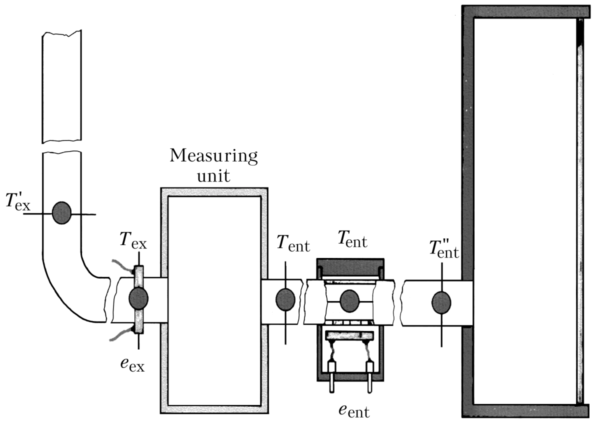

Fig. 1. Measurement system. The space to the right of the window-frames is connected with the ventilation channel through the airway and the measurement cell. Exit and entrance temperature and humidity sensors (T_{ent}, T_{ex} and e_{ent}, e_{ex}) are placed at different points of the airway.

The natural frequency of the resonator is related to the atmospheric dielectric constant in the following way:

$$f_r = \frac{c}{4\pi\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{\chi}{R}\right)^2 + \left(\frac{\pi n}{L}\right)^2} .$$

This equation is valid for a cylindrical resonator; c is the speed of light, ε is the relative dielectric constant, μ is the relative magnetic permeability, R is the resonator radius, χ is the root of the Bessel function for this type of the wave, L is the resonator length; n is the number of half waves multiple of this length.

In vacuum (at the pressure $\le 10^{-3}$ mm Hg) ε is about unity. With the high degree of reliability, the relative magnetic permeability can be also thought roughly equal to unity, but a small difference proves to be a significant factor for propagation of electromagnetic waves. The refractive index

$$n = \sqrt{\varepsilon} = \sqrt{1 + (\varepsilon - 1)} \approx 1 + (\varepsilon - 1)/2$$

is close to unity as well. Therefore, for a thorough consideration of small deviations from unity, the refractive index is usually measured in N-units, $N = (n - 1) \cdot 10^6$. In the atmospheric surface layer, N varies from 150 to 400.

The difference of the generators' frequencies $\Delta f = f_v - f_a = N \cdot 10^4$ Hz is calculated at the exit of the refractometer. Here f_v is the frequency of the generator with the vacuum resonator; f_a is the frequency of the generator with the open resonator connected with the atmosphere. The unit N always corresponds to the frequency ~ 10^4 Hz.

Thus, if both of the resonators are operated with the same type of the wave and have the same dimensions, and one of them is evacuated, whereas the other is connected with the atmosphere, then the difference in their frequencies is a measure of the refractive index. It is just this factor that makes the main advantage of the used method, because the errors caused by additional transformations of the information about the refractive index are excluded.

One more positive factor is the frequency stability of the generators and, consequently, high sensitivity of determination of N, because the main error depends on the accuracy with which the stabilization system tunes the generators to the natural frequencies of the resonators.

The device uses the Grain scheme,[2] but to provide for high stability of the UHF generators, highly efficient automatic-frequency stabilization system is used. Some measures were undertaken to prevent emission of the UHF energy from the measurement resonator into the open air. This allowed us to markedly increase the Q-factor of the resonator along with the efficiency of the automatic-frequency stabilization system.

The volume resonators are made using a single unit of a metal (invar) with a low thermal expansion factor and housed in a passive thermostat, what markedly decreases the effect of the ambient temperature on the measurement accuracy. During the operation, the high-frequency oscillations connected with the 3D turbulence are to be damped. Therefore, all the measures listed above are needed to compensate for the inevitable loss of the signal and to reliably measure very small variations of N.

The refractometer consists of the following units:

1) the UHF system, which has two generators with the reference (vacuum) and measurement (open) resonators, two ferrite valves, two directed couplers, two detector sections, and a mixer;

2) two automatic-frequency systems, each consisting of a modulation generator, broadband amplifier, phase detector, dc amplifier, and intermediate-frequency amplifier.

The sources of energy in the UHF system are Gunn diode generators. The volume cylindrical resonators operate mostly on the TE_{011} type of oscillations. This type of oscillations allows obtaining the highest Q-factor, which determines the stability and sensitivity of the refractometer. Using the automatic-frequency system in both (reference and measurement) channels, the frequencies of the generators are strictly related to the natural frequencies of the corresponding resonators. Both automatic-frequency systems are identical.

The above-considered instrument has the following errors.

1. The systematic error caused by variation of the frequencies of the reference and measurement resonators due to the temperature gradient between them. In

Ref. 3 it was shown that if the resonators are made as a single invar unit, the maximum possible amplitude of the temperature wave is 0.02 K. With the use of a thermostat, it can be suppressed down to 0.007 K; this value corresponds to the resulting error $\sim 7 \cdot 10^{-9}$.

2. The systematic error due to the time lag of the automatic-frequency system. When evaluating this error, it turned out that the deviation of the generator frequency from the natural frequency of the resonator at the automatic-frequency system turned on to be below $5 \cdot 10^2$ Hz, and as the channels are identical, the frequencies in them drift in the same direction and the total error does not exceed 10^2 Hz. Thus, the error caused by this factor proves to be roughly equal to 10^{-8}.

3. The random error caused by variations of the frequencies of the reference and measurement resonators due to their mismatching with the external waveguide tracts at variation of the refractometer temperature. This error is minimized by continuous (without turning off) operation of the refractometer and thermostatic conditions provided for the resonator unit with the waveguide tract; the value of this error is less than $5 \cdot 10^{-9}$ as the temperature varies from 250 to 330 K.

Thus, with the allowance made for the above-said, the absolute error is $\le 10^{-8}$, that is, ± 0.01 N-units. These characteristics of the refractometer can provide for the metrological support when measuring meteorological parameters.

The dependence of N on the meteorological parameters can be expressed as follows:

$$N = k_1 \frac{p}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2},$$

where T is the absolute temperature; p and e are the partial pressure of dry air and water vapor, respectively.

The coefficient k_1 characterizes the polarizability or the effect of displacement of electric charges of dry air molecules; the coefficient k_2 characterizes the same effect but for water molecules; k_3 determines the dipole moment of water molecules, their orientation, and, consequently, polarization. To calculate N from the meteorological parameters, the equation $N = 77 \cdot 6/T(p + 4810\, e/T)$ is usually used, whose rms error is 0.5%, i.e., 1.5 N-units. This error is caused by the inaccuracy in the empiric coefficients k_1, k_2, and k_3. Other sources of errors in determination of N are the measurement errors of the parameters p, T, and e. Therefore, the advantage of the refractometer is obvious, because it allows the measurements to be carried out without measurements of the meteorological parameters. The technical improvements undertaken along with the continuous mode of measurement of the RI dynamics allows the state of the atmosphere to be monitored based on very small variations of N and the method that can be called microwave ultra-refractometry of the atmosphere.

The first results demonstrating that the dynamics of N is an interesting object for predicting thunderstorm processes in the geo- and troposphere were obtained on October 4, 1994 during the passage of a cyclonic shower. During a day, 12-minute records with the step of 2 s were obtained. The character of recording (Fig. 2) was different, and the amplitude of N spikes at some moments in time was about 10% of the normal level. This was observed on the eve of the strong destroying earthquake on Shikotan Island. In addition, the values of N and atmospheric pressure were recorded during the day with the half-hour interval (Fig. 3). For a comparison, Fig. 3 demonstrates the behavior of these parameters on October 5 of 1994 and on the calm day of October 12 of 1994 during the passage of the cyclone similar to that on October 4.

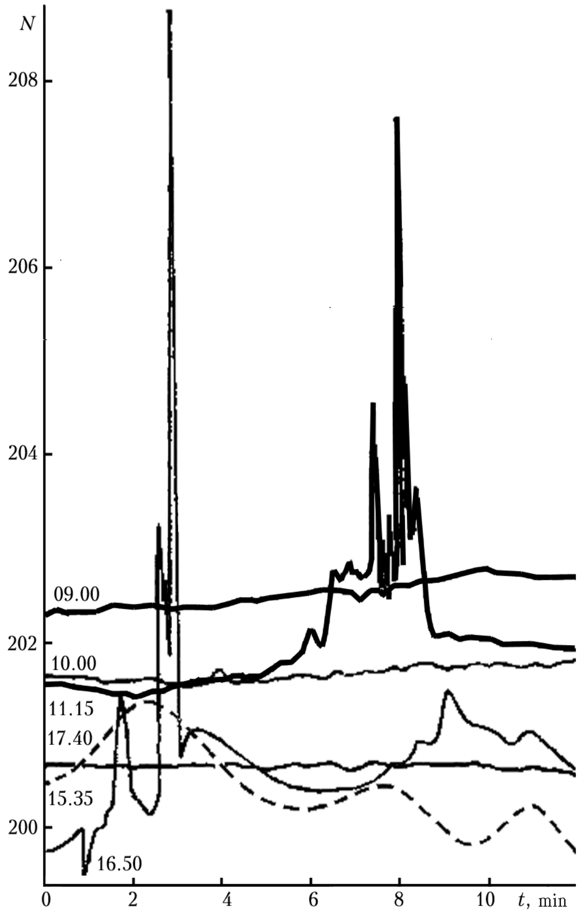

Fig. 2. Twelve-minute fragments of the refractive index dynamics recorded on the eve of the earthquake on the Shikotan Island at the night on October 4–5 of 1994.

The obvious difference in the behavior of N stimulated long-term continuous measurements and development of the optimal measurement technique. Data were collected continuously with the smallest possible step of 1 min, and digital devices were connected and started by a timer.

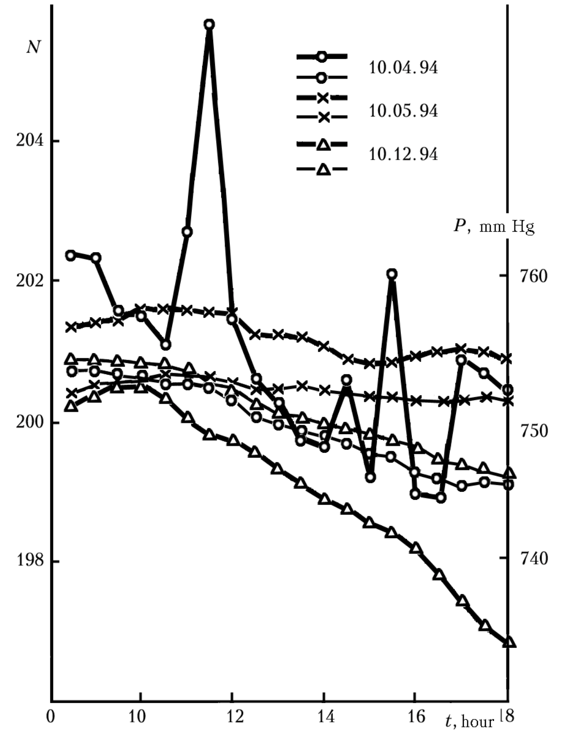

Fig. 3. Example of the records of the refractive index and atmospheric pressure with the half-hour interval. The bold curves correspond to the refractive index (left ordinate), and normal curves are for the atmospheric pressure (right ordinate).

Observations

For the period of observations since October 1994 until now, about 2.5 millions of readouts have been stored; sometimes round-the-clock observations were conducted. Analysis of the full set of records shows that oscillations of the refractive index intensify before atmospheric or Earth's cataclysms, such as the approach of deep cyclones and typhoons or their passage near the observational zone, as well as oncoming magnitude 5 and higher earthquakes. All records were identified against the NEIC data and satellite weather maps. For the time of continuous observations, about 100 magnitude 5 and high earthquakes occurred at different points of the Earth, as well as several tens of atmospheric phenomena, including large cyclones, typhoons, and storms. The correlation between the recorded data and the following natural phenomena is very high. Incomplete correspondence to the NEIC data is connected with the fact that the measurements were mostly conducted in daytime. The range of RI fluctuations vary from less than 10^{-3} to several Hz.

Figure 4 illustrates the correlation of the refractive index with the humidity e measured in the resonator and the temperatures at the resonator entrance and exit. High correlation is observed between the refractive index and the humidity in the resonator.

Roughly at 02:30 p.m., all curves demonstrate sudden “intrusion” of high-frequency oscillations of almost all parameters, except for temperature at the entrance of the measurement system. This record was obtained on the eve of violent 5.5 magnitude earth tremors in Japan. After 03:30 p.m., some signs of oncoming Typhoon Tina are observed.

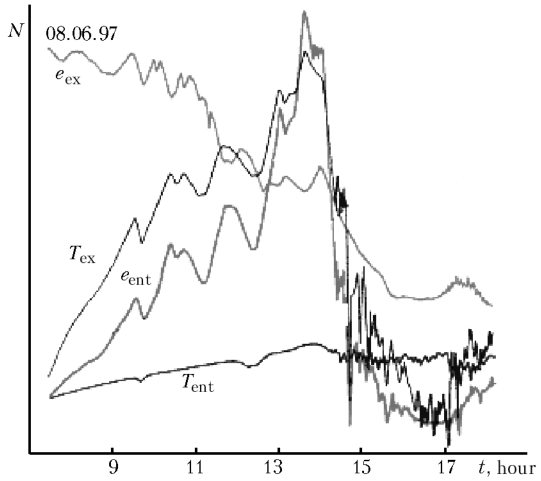

Fig. 4. Correlation between the refractive index and humidity in the resonator, as well as the temperature at the resonator entrance and exit.

Of great interest is the effect of “opposing” oscillations of the temperatures at the resonator entrance and exit. This effect is observed at a certain distance between the temperature sensors against the background of the intense RI fluctuations and is likely connected with the thermo-acoustic oscillations. Similar effect is observed in gaseous helium in an open-end tube with temperature difference.[9] Longitudinal oscillations arise in the tube. The energy of these oscillations may be high enough to transfer a sufficient amount of heat to the region of lower temperatures. The parameter N fluctuates in phase with the temperature at the resonator entrance and in antiphase with the temperature at its exit. The half-wavelength of these oscillations can be determined from the maximum of temperature anti-oscillations. In winter, this value is three to four times higher. Thermo-acoustic oscillations are indicative of the atmospheric activity.

Discussion

The current geophysical concept is based on the idea that the outer layer of the Earth − lithosphere − consists of approximately fifteen rigid plates carrying the upper crust that move over the underlying mantle. Geological structures are formed due to the tectonic motions. As this takes place, surface breaks binding the corresponding geological structures are formed in the upper Earth's layer for a long time. The intensity of tectonic motions determines the seismic activity of the regions, where they are most pronounced. Now it can be thought established that mid-oceanic ridges, island arcs, and other such formations are the results of intense tectonic motions. Slow motions are sometimes accompanied by displacements along the breaks thus causing earthquakes.

It should also be kept in mind that the Earth is a part of the system of heavenly bodies. The Moon produces the strongest effect on the Earth. The gravitational forces of attraction give rise to tides. Therefore, the outer layer of the Earth is in the variable force field. Twice a day significant vertical shifts occur in the Earth's crust along the break lines due to tidal forces. In such cases, local motions of the masses may be provoked that disturb the normal distribution of the density over the surface. In other words, the local density comes to some "excited" state accompanied by the jump of the force of gravity. This jump gives rise to the local jump of the atmospheric density. This causes generation of a train of infrasonic oscillations, which, propagating without losses, modulate the fields of humidity, temperature, and pressure on their path. Generally, this manifests itself as fluctuations of the refractive index.

The lifetime of the "excited" state of the lithospheric matter, in its turn, is determined by its mechanoelastic properties. Under the effect of gravitational forces of the Earth–Moon attraction, the lithosphere displaces along the break line. Some "excess" of the mass may arises in this region due to fall or flow of the matter. Once the tide terminates, a spot with the stress of the underlying rocks arises at this place under the effect of giant pressure forces. The stress is accumulated here until a break arises at the depth of several kilometers and "slippage" of the rocks along the breaks relieves the stress.

Regional short-term motions of atmospheric masses cause perturbations of the gravitational force up to 15–20 μgal. And vice versa, if such a change is stimulated by the "excess" mass, then perturbations are generated in the atmosphere. Sometimes, a deficit, rather than excess, of mass also may arise due to the same forces. Then the appearance of a mesoscale anomaly becomes possible because of local depression of atmospheric pressure. The normally stratified atmosphere comes from the stable state into the excited one and becomes an additional source of atmospheric infrasound.

Thus, it can be concluded that the local excess of mass or its deficit may be a center of the future earthquake. This conclusion is confirmed by the fact that most earthquakes occur along tectonic break lines, in the zones near continents, near island arcs and other similar structures. The seismicity of the Pacific Ocean is concentrated just in these zones, where most surface earthquakes occur and more than 80% of the total seismic energy of the Earth is released. Various atmospheric anomalies also arise in these regions.

The atmosphere can warn about local changes in the lithosphere. A signal comes to such a detector in the form of infrasonic oscillations arising due to local jump of gravity Δg. Thus, monitoring minor changes in the state of the atmosphere, we can provide for monitoring of fast geophysical processes. Now there are data on transformation of the atmosphere and appearance of extended linear cloudy anomalies over the breaks.[6]

In recent years, numerous evidences of variation of the gravitational force of the Earth in time have been accumulated.[7,8] Geodynamic grounds for measuring the force of gravity are organized in the Southern California, Japan, Northern Ireland. The measurements are conducted by simultaneous leveling of the Earth's surface. On these grounds, variations of the force of gravity caused by a set of factors preceding or accompanying volcanic eruptions are recorded. In some cases, the changes were observed in the gravitational field of the Earth before and after strong earthquakes. These changes correlate with variations of the surface heights.

Finally, it should necessarily be noted that some fine measurements require local variations of the force of gravity to be taken into account. For example, when measuring the vapor pressure by liquid manometers, it is necessary to introduce corrections for variations of the gravitational field depending on the geographical position.[10] An importance of such an approach is confirmed by the fact that spring-type and pendulum gravimeters allow reliable recording of variations caused by fluctuations of air density in the region of observations.[11]

The estimated possible variations of the force of gravity with allowance for the size of seismic centers[13] on the spots with increased density of the excess mass considerably exceed 10^{-7}–10^{-8} of the relative level, which can be detected by spring-type gravimeters. In recent years, much attention has been given to the study of local variations of the gravitational potential on geodynamical grounds. These studies are aimed, first of all, at revealing the possibility of obtaining the information on motions of masses in the Earth's crust before earthquakes from variations of the force of gravity on the surface.[12]

Conclusions

To confirm the need in such studies and stationary observations in the future, automated collection and processing of the corresponding information should be organized.

A wide observational network will give an answer to the question on whether or not infrasonic atmospheric oscillations stimulated by a local jump in the force of gravity bear information on the ongoing catastrophe? The positive answer confirms the validity of the proposed mechanism, which, however, does not reject the existing ideas on the development of the earthquakes. The proposed point of view also does not reject the idea that inner gravitational waves generated by different tropospheric perturbations are an interesting object for meteorological observations.

It is possible that atmospheric perturbations are responses to manifestations of gravitational waves generated by the accelerated motion of masses in the upper mantle during the action of tidal forces. According to Ref. 14, periodic gravitational waves can affect complex systems and parametrically give rise to structure-forming effects. The solution to the problem of detection of gravitational waves may possibly be found on the way of parametric amplification of the effect of gravitational waves on a system. By the difficulty of detecting, the gravitational waves can be compared with the detection of direct absorption of ultrasound by a nuclear spin-system in the solid-state physics.[15] Although these problems are characterized by significantly different complexity, a certain analogy between them can certainly be mentioned.

Thus, the coefficient of lattice (background) absorption in good acoustic materials has a value of the order of 10^{-2} cm^{-1}, whereas the absorption coefficient for ultrasound due to spin-phonon bond does not exceed 10^{-7}–10^{-8} cm^{-1} and calls for very sensitive methods to be measured. Therefore, only a few experimental works aimed at measurement of this coefficient have been done until so far. At the same time, the interaction of acoustic waves with a nuclear system is successfully studied with an indirect method through saturation of a nuclear spin-system with the electromagnetic field with simultaneous effect of the ultrasound.[16–18]

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