Macroscopic nonlocal correlations in reverse time by data of the Baikal Experiment

S Korotaev[1,2]**, N Budnev**[3]**, V Serdyuk**[2]**, E Kiktenko**[1,2]**, D Orekhova**[2] **and J Gorohov**[4]

[1] Bauman Moscow State Technical University, Moscow, Russia

[2] Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, Troitsk, Moscow Region, Russia

[3] Institute of Applied Physics, Irkutsk State University, Irkutsk, Russia

[4] Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences, Troitsk, Moscow Region, Russia

E-mail: `korotaev@igemi.troitsk.ru`

Abstract. Consideration of macroscopic entanglement in the framework of action-at-a-distance electrodynamics leads to rather simple description of macroscopic quantum nonlocal correlations between random dissipative processes in the source and detector. These correlations have both the retarded and advanced component. The latter means correlation in reverse time. Therewith the advanced component through an absorbing medium exceeds the retarded one. For diffusion entanglement swapping the retardation and advancement can be very large. These correlations are detected at extremely low frequencies and characterized by the large time shifts. But these experiments are very difficult in a usual laboratory because of various local interferences. The experimental problem is elegantly solved under deep-sea conditions. The Baikal long-term experiment has started in 2012 at Baikal Deep Sea Neutrino Observatory. The long-term observations demonstrated that detector signals respond nonlocally to the random heliophysical processes. This nonlocal correlation proved to contain considerable time reversed component, exceeding time respecting one. Next, advanced nonlocal correlations of the detector signal with two regional random source-processes: strong earthquake and low frequency macroturbulence in the lake were revealed. In fact this means observation of the random future. The possibilities of the forecasts of random components of solar and hydrological activities on correlations in reverse time have been demonstrated.

1. Introduction

According to quantum principle of weak causality [1,2] for the random processes in the entangled systems advanced (time-reversed) correlations through time-like interval are possible. More precisely, there should be symmetrical in the time shift retarded and advanced correlations. In electromagnetic interaction, the absorption efficiency of the advanced Wheeler-Feynman field is less than the retarded one [3]. This leads to the fact that the level of advanced correlation through the absorbing medium exceeds the level of retarded one. Strict calculation of nonlocal correlations for macroscopic systems is possible only for particular idealized physical models. In experiments on the study of non-local correlations of large-scale dissipative processes used the equation of macroscopic entanglement, obtained on the basis of the absorption electrodynamics of Wheeler-Feynman and its quantum generalization (e.g. [4]). This equation was partly tested

theoretically with the spin gas model and experimentally (with the magnetosphere source) [4]. This "partialness" was in the fact that it was possible to demonstrate the correspondence of the response magnitude of a probe-process in the detector to the theoretical prediction; but the time shift, which is determined in natural macro-processes by extremely complex diffusion entanglement swapping, is theoretically impossible to calculate yet. Therefore experimental estimates of the time shifts are important for the framework of the theory development and the applications as well.

Experimental problem is to establish a correlation between the source-process and completely isolated from the classical local influences probe-process in the detector. Although many natural random dissipative processes can be such sources, due to the principle of monogamy of quantum correlation, their number, causing a noticeable response of the detector is small. Long-term experiments in different laboratories and with different types of detectors have shown that solar activity is the dominant source. Global geomagnetic activity and regional synoptic activity are less pronounced (the former, however, is convenient for quantitative interpretation, and in combination with solar one has allowed to verify violation of the steering in equality, proving nonlocality of correlations. The possibility of forecasting of the random components of solar and geomagnetic activity on the nonlocal correlations has been proved [4].

The greatest nonlocal correlations are observed at extremely low frequencies (over periods of several months), which requires long-term experiments under highly stable conditions with great difficulty achieved in a usual lab. Therefore a new experiment was launched in 2012 at the Baikal Deep Sea Neutrino Observatory. Baikal is the deepest lake in the world ant its thick and calm water layer provides good protection from the classical local influences. In particular, already at the depth of several tens of meters natural thermostating is better is better than that attainable in usual lab conditions. In addition, it is easy to implement measurements at different depths, which allows investigating the nonlocal response from different sources (including the regional ones: earthquakes and hydrosphere macroturbulence) with an adjustable by absorbing water layer signal-to-noise ratio.

In the current paper we at the beginning review setting of the Baikal experiment and its basic results for the first five years, and then we consider recent results in more detail.

2. The Baikal Experiment ant its basic results

As the detectors of macroscopic nonlocal correlations the electrode-type ones were selected, this, as previous experience had shown, proved to be the most reliable for long-term operation. The probe- process in them is spontaneous (not caused by any classical local influences) variations of self-potentials of a pair of electrodes in the electrolyte. Nonlocal correlations are manifested in the nanoscale entropy change of the liquid phase of the double electric layer; the theory of the detector [4] associates the change in entropy with the measured signal of the self-potential difference. The detectors represent matched pairs of weakly polarized metrological silver-silver chloride electrodes HD-5.519.00 with a small (several centimeters) distance between the contact windows. These electrodes have been selected as the best in the world due to the insensitivity of their own self-potentials to the physicochemical environmental conditions.

The experimental setup is deployed at a depth of 1367 m and includes two electrode detectors on different horizons: Ut (top) and Ub (bottom), environmental monitoring equipment and an electronics unit designed for one-year autonomous operation. The relative error of detector signal measurements is not more than 0.01%. Every year in March, the setup is lifted to the ice for data reading, battery changing and the necessary modifications. In the final configuration, the detector t is located at a depth $z = 47$ m, Ub– at $z = 1337$ m. The experiment also includes synchronous measurements with a remote electrode detector at a land laboratory setup in Troitsk (Ul, $z = 0$). The data are processed (together with indices activity of heliogeophysical source-processes) by various methods of spectral, correlation and causal analysis. Detailed description

of experimental technique and data processing technique are presented in Refs [5,6].

The results of several annual series have confirmed the conclusion about the dominance of solar activity in the correlations of the detector signal with external processes. Therewith the detector signal is correlated with the random component of solar activity, which is represented in its spectrum by intermittent variations (Riger variations). They do not have a certain period and occupy a band of periods about from 100 to 500 days. On the contrary, the 27-day variation determined by the rotation of the Sun, which has the largest amplitude in all indices of solar activity, causes almost no response of the detector. The correlation of the detector signal with solar activity has a retarded and approximately symmetric by time shift advanced component, the latter is always greater. The main maximum of correlation is observed at the advancement of order of 100 days, and this value varies significantly from year to year.

The signals of the different detectors are highly correlated at horizontal spacing of at least up to 4200 km. No causal connection was found between the signals of the detectors on the Earth surface. This connection appears if the detectors are separated vertically by a shielding layer of dense matter (water); it is directed from the Earth surface downwards and is accentuated by increasing the layer thickness. Therewith the correlation and causality are divided into approximately symmetrical by time shift ($\pm$20-30 days) retarded and advanced components. The advanced maximum of the correlation is always greater. The greatest asymmetry of maxima is observed at the greatest vertical spacing of detectors: the Earth's surface – the Baikal floor.

In relation to solar (and geomagnetic) activity, Ut detector has the highest signal-to-noise ratio (in Ul there is noise from atmospheric processes, while in Ub the signal is attenuated by the total water column. On the other hand, it is due to the significant shielding from solar-geomagnetic and hydrodynamic activity (the latter covers only the upper active layer of the lake to the depth of approximately 500 m) Ub detector has a high ratio signal-to-noise in relation to lithospheric processes that is earthquakes.

The Baikal Rift is a seismically active zone, but on the scale of the experiment quite powerful earthquakes in the vicinity of the setup are a rare event. During the time of the observations, there was one such earthquake (22.12.2013, magnitude of 5.6), which caused a clear disturbance in the almost noiseless Ub record, including the advance signal splash 6 days before the event., while in Ut the size of the disturbance was comparable to the noise.

A weaker, but permanent source is macroturbulence in the active layer of the lake. By the signal-to-noise ratio, the Ut detector is optimal. The spectra of contributions to the signal from solar activity and macroturbulence overlap, which complicates the task. Nevertheless, it was found the presence of almost symmetric by time shift correlations of Ut with indices of hydro-thermodynamic activity, the advanced maximum was always greater than the retarded one. Successful (although forced short) experimental forecasting series were obtained.

3. Recent results
In this section we consider results of measurements with Baikal deep-sea setup during 2016–2018. In the course of description the similarities and differences with specific previous results are indicated.

We begin with correlation between the dominant source-process that is solar activity with optimal detector Ut. The experimental conditions allowed us to combine a series of measurements 2016/2017 and 2017/2018 with Ut detector in a single two-year series with accurate preservation of the signal level and with a negligible time gap. As before, the solar radio wave flux R at a frequency of 2800 MHz, corresponding to emission from the level of the highest entropy production in the solar atmosphere (the upper chromosphere–lower corona, where magnetosound waves dissipate) is taken as the solar activity index. Note that the experiment began in 2012 at the maximum of 11-year cycle of solar activity, while the two-year series 2016-2018 fell on a time close to the minimum of this cycle.

Based on the theory and previous experimental results [4-9,11], the following features of the correlation of Ut with R should be expected. First of all, as with any large-scale process, macroscopic nonlocal correlations are greatest at extremely low frequencies (over periods of several months). Further, for random source-processes, according to the quantum principle of weak causality, there are time-symmetric retarded and advanced correlations. Due to the fundamental asymmetry of the absorption efficiency of the retarded and advanced signals by the intermediate shielding medium, the level of the advanced correlation is higher than the retarded one. As a result, the main response of the detector signal causes long-period variations in solar activity with a large random component that is aforementioned intermittent variations observed in the range of 100–500 days [12]. According to the data of the two-year series, sufficiently reliable spectral estimates somewhat reduce this range from the long-period side to about 400 days. On the contrary, highly determined variations of R due to the rotation of the Sun (a period of about 27 days with its harmonics and subharmonics), despite their large amplitude, should cause a weak response in the signal Ut. The correlation function $r(\tau)$ should have symmetric retarded and advanced maxima at the value of time shift $|\tau|$ of the order of one hundred days, and the advanced maximum should be greater than the retarded one. The expected ratio of the advanced and retarded maxima $r^{adv}/r^{ret} \approx 1.1$.

In Figure 1 synchronous amplitude spectra of Ut and R in the period range of $10 - 461$ days are presented.
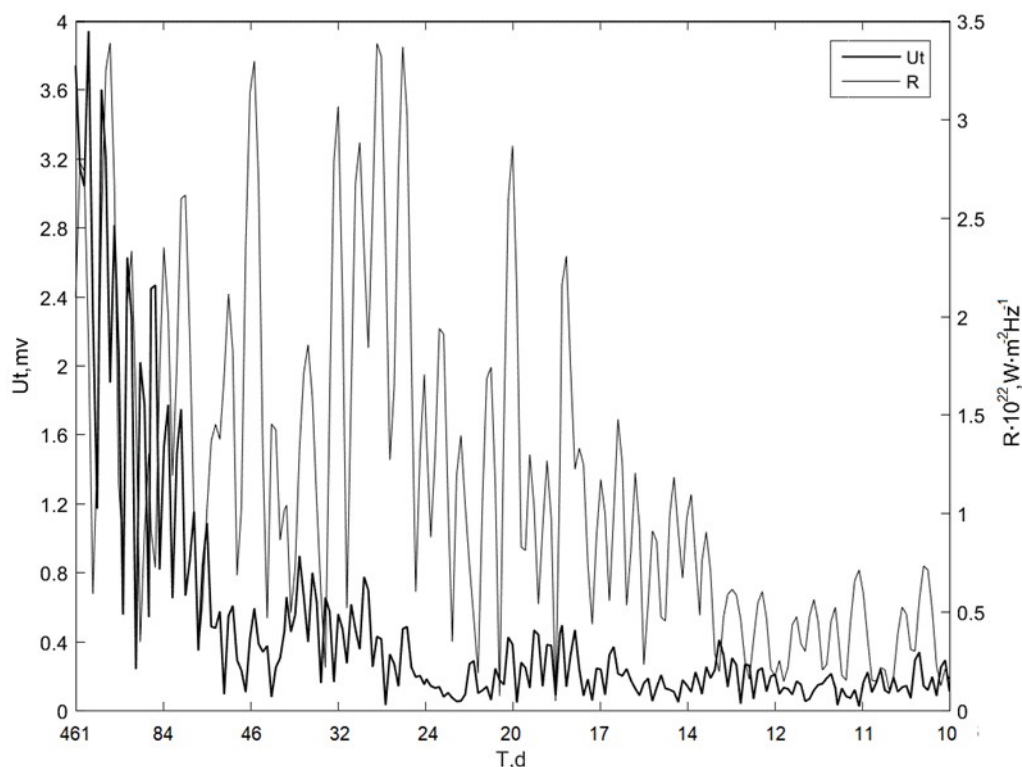

Figure 1. Amplitude spectra of the detector signal Ut and solar radio wave flux R (2016/2018).

The response of Ut to variations of R determined by the rotation of the Sun is indeed very weak, but it is significant and is clearly visible on the left side of Figure 1, corresponding to the range of random quasi-periods of intermittent variations. The greatest similarity of spectra is observed in the range $379 > T > 83$ days. For further analysis, the data were subjected to bandpass filtering in this range.
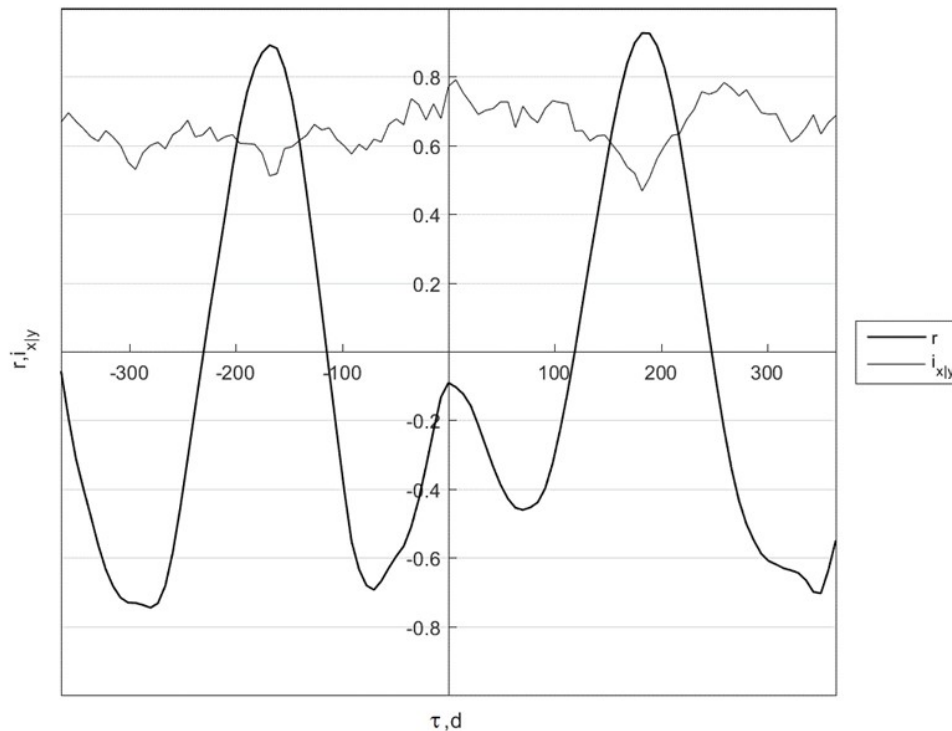
Figure 2. Correlation function r of the detector signal Ut and solar radio wave flux R and their independence function $i_{Ut|R}$. The τ is time shift in days. $\tau < 0$ corresponds to retardation of Ut relative to R, $\tau > 0$ – to advancement.

In the calculation of the correlation function, a four-year series R was used, beginning one year before the beginning of the Ut series and ending a year after its completion. Thus, in the calculation of the correlations for all τ in the range of ± 1 year, the full two years of Ut series was used, which ensured the equivalence of all estimates. The result is presented in Figure 2.

R, $\tau > 0$ – to advancement. With almost symmetric shifts of τ, two main correlation maxima are observed: the retarded one: $r^{ret} = 0.88 \pm 0.03$, $\tau = -165^d$ and the advanced one: $r^{adv} = 0.95 \pm 0.02$, $\tau = +180^d$. The advanced correlation is greater than the retarded one: $r^{adv}/r^{ret} = 1.08 \pm 0.04$. There is a predicted asymmetry, but its quantification is not very reliable. To take into account a possible nonlinearity it makes sense to calculate also a more adequate response measure (equally suitable for both linear and any non-linear connections) —the independence function, defined through conditional and marginal Shannon entropies: $i_{Ut|R} = S(Ut|R)/S(R)$. The independence function in the first approximation behaves inversely to the correlation function; the expected ratio of the corresponding independence minima $i^{ret}_{Ut|R}\big/ i^{adv}_{Ut|R} \approx 1.1$. In Figure 2 the independence function, calculated by the same data, is also shown. The main correlation maxima correspond exactly to the main minima of independence: $i^{ret}_{Ut|R} = 0.51^{+0.02}_{-0.01}$ and $i^{adv}_{Ut|R} = 0.47^{+0.00}_{-0.01}$. In the independence functions that take into account nonlinearity, asymmetry is more reliably expressed: $i^{ret}_{Ut|R}\big/ i^{adv}_{Ut|R} = 1.09^{+0.02}_{-0.01}$.

Thus, all the supposed characteristics of nonlocal correlations with solar activity are confirmed by the experiment. However, in these suppositions, the most uncertain, ordinal, estimate was the time shift of the maximum correlation (minimum of the independence function). Therefore, the experimentally obtained specific value of this shift under specific conditions (phases of the solar cycle and the depth of the underwater detector) is important.

It allows solving the problem of forecasting of random (!) R variation. Previously, we developed two self-learning software-implemented predictive algorithms: the current regression [5,6] and convolution with the current impulse transient response [4]. The latter is more perfect because it takes into account the non-Markovian nature of processes dependence, but it requires the duration of the training interval by an order of magnitude greater optimal lead time of the forecast (determined by the position of the global maximum of the correlation function, in given case 180 days). The former is less demanding on the length of the training interval, but it cannot be applied in this case because of the strong reduction in the length of the series of the above-mentioned bandpass filtering. But the fact that Ut really predicts R is easy to see by simply shifting the filtered series (Figure 3).
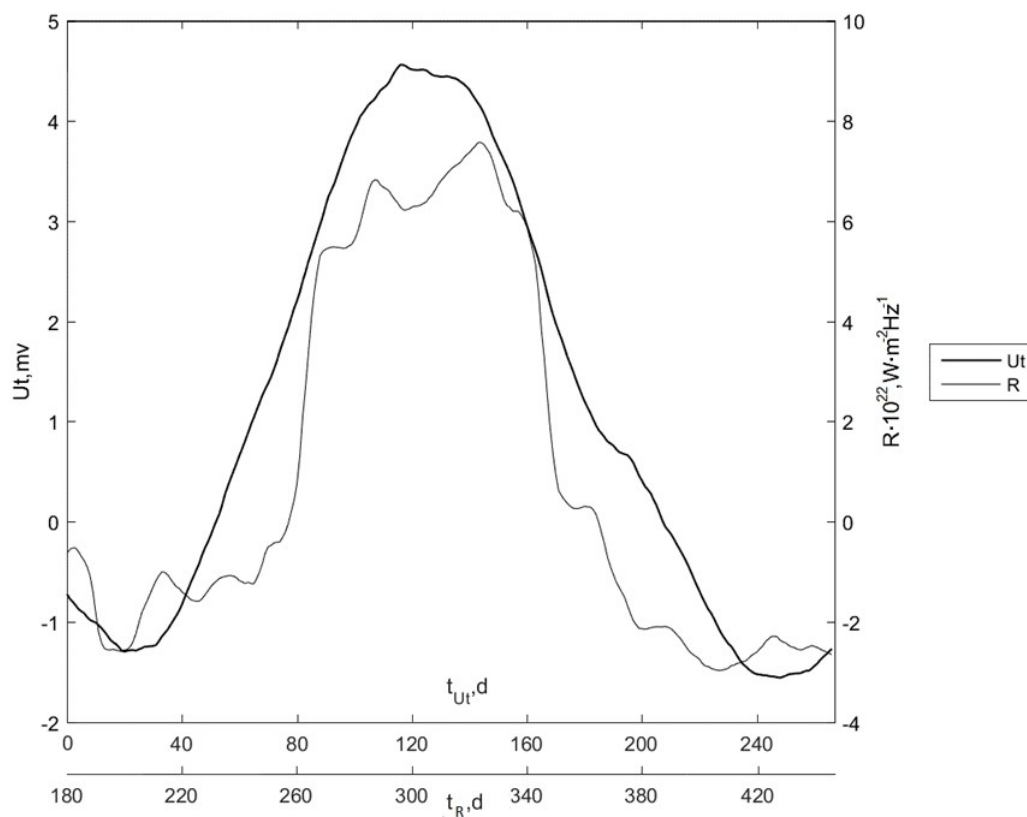

Figure 3. Ut approximately forecasts R (relative to the average biannual level) with advancement 180 days. Starting time November 4, 2016.

Turn now to another source-process: macroturbulence in the active layer of the Lake Baikal. It is typical random dissipative process. Large turbulent vortices dissipate by cascade decay into smaller and smaller ones, and finally into heat. Practically macroscopic nonlocal correlations are observed at extremely low frequencies (on periods of the order of months), therefore the interest for the research is macroturbulence. In the Baikal, macroturbulence in as a random process in the most pure form takes the period range between synoptic and seasonal variations, that is, from about 10 days to a year; in the lower part of this range, an appropriate response of the macroscopic nonlocal correlation detector should be expected. Turbulence is a dynamic phenomenon, although it is technically easier to observe it in variations of temperature rather than velocity. Therefore, in the Baikal experiment, the response of the detector of macroscopic correlations Ut to variations in the temperature of the active layer was previously mainly studied.

The response to velocity variations has also been studied, although only on one near-surface horizon $z = 20$ m. As a result, the nonlocal correlation was found, exceeding the retarded one, with a maximum at advancement 20-45 days, and the forecasting series were obtained using the current regression method [6,7].

At the stage of the 2017/2018 experiment, 11-month measurements of the flow velocity were carried out by "Infinity" devices on two horizons: 100 and 500 m, the average between which is a satisfactory characteristic of the process in the entire active layer that causes a response in the Ut detector signal. Although the influence of solar activity on the Ut signal is dominant, the year of its minimum 2017/2018 is favorable for highlighting the response to hydrodynamic activity.

In Figure 4 the amplitude spectra of the detector signal Ut and the average velocity V are shown. The greatest similarity of the spectra is observed in the lower part of the range in the period band $130 > T > 28$ days.
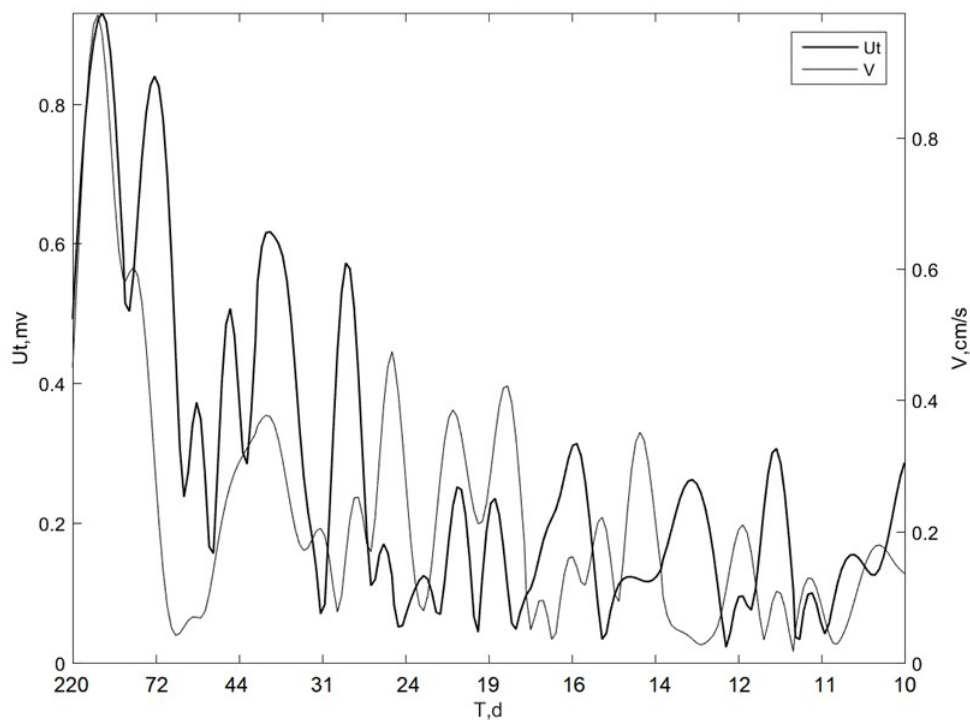

Figure 4. Amplitude spectra of the detector signal Ut and average velocity V (2017/2018).

At the same time, in this band in Ut there are three spectral maxima at the periods of 72, 52, and 43 days, which have no correspondence in V and, obviously, associated with another source — solar activity. This is confirmed by the comparison of Ut with the synchronous spectrum R (Figure 5).

The contribution of solar activity to the signal is a hindrance, however, after the bandpass filtration $130 > T > 28$ days Ut correlation with V turned out to be quite high. In figure 6 the correlation function $r(Ut, V)$ in the time shift range $\tau \pm 62$ days is shown. The greatest correlation equal to 0.890 ± 0.008 is observed at advancement of Ut relative to V by 39 days. The maximal magnitude of advanced correlation is significantly greater than the maximal magnitude of retarded one: $|r^{adv}/r^{ret}| = 1.20 \pm 0.01$. Difference between signs of r^{adv} and r^{ret} is simply due to the phase sensitivity of V. This could have been avoided by using the energy index (proportional to V^2), but we prefer not to do this so as not to allow nonlinearity distorting the magnitudes of the correlations.
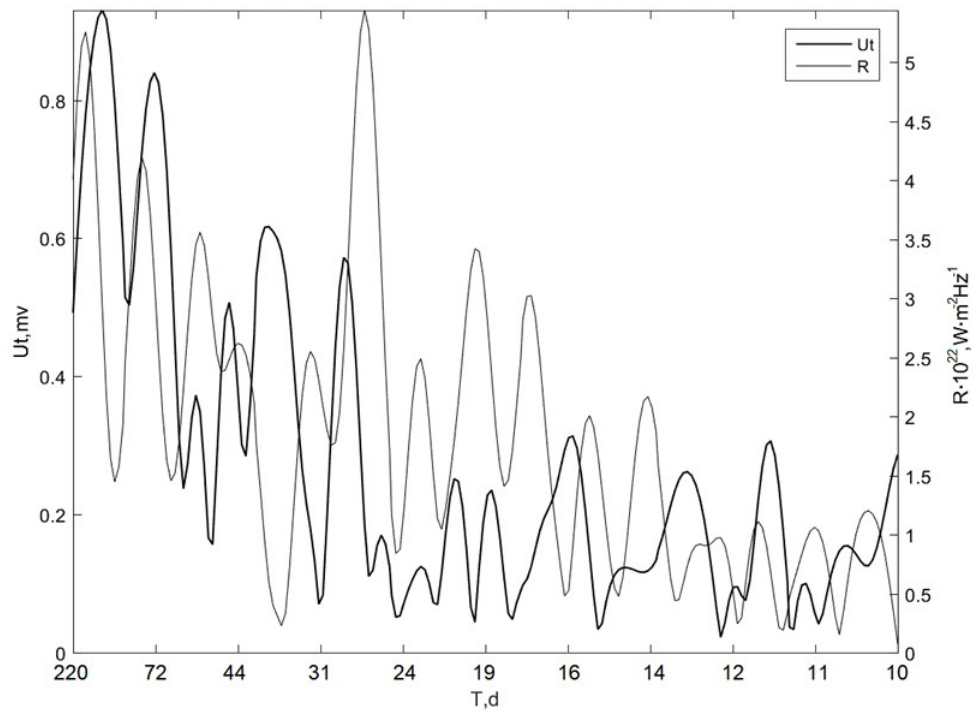
Figure 5. Amplitude spectra of the detector signal Ut and solar radio wave flux R (2017/2018).

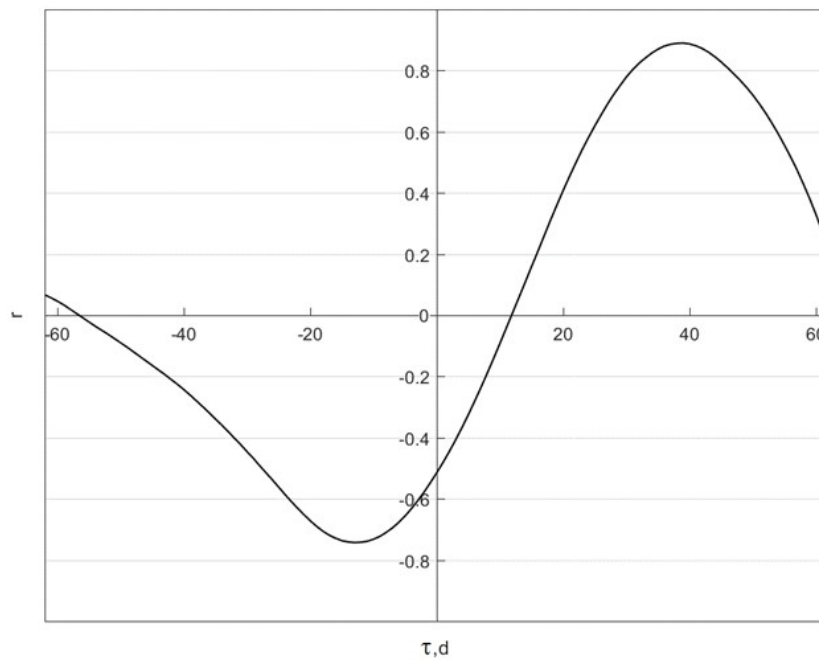**Figure 6.** Correlation function r of the Ut and V. $\tau < 0$ corresponds to retardation of Ut relative to V, $\tau > 0$ – to advancement.

Having the 11-month series of observations V and applying the above optimal bandpass filtering, which greatly reduces its length, we can yet demonstrate the forecast of random variation V, although only with algorithm of the current regression, less demanding to the length of the training interval. In this algorithm, the regression coefficient V by Ut is calculated at the primary training interval with a shift of 39 days, which is then used to calculate the first forecasted value. Since we are simulating a real forecast (without looking into the future), the last value used is V at the time of the forecast, and Ut is 39 days ago. In the next step (hour in given case), the training interval is pulled forward and the next value is predicted with the same 39 day's advancement, and so on. The current variable regression takes into account nonstationarity and possible nonlinearity, although due to the missing last 39 days of Ut, this accounting cannot be complete. The result of the forecast is shown in Figure 7. Due to the long training interval and, accordingly, the short remainder of the series to test the forecast, a demonstration of the forecast in Figure 7 does not look very impressive. But the accuracy of the forecast ϵ is sufficient for all practical purposes.

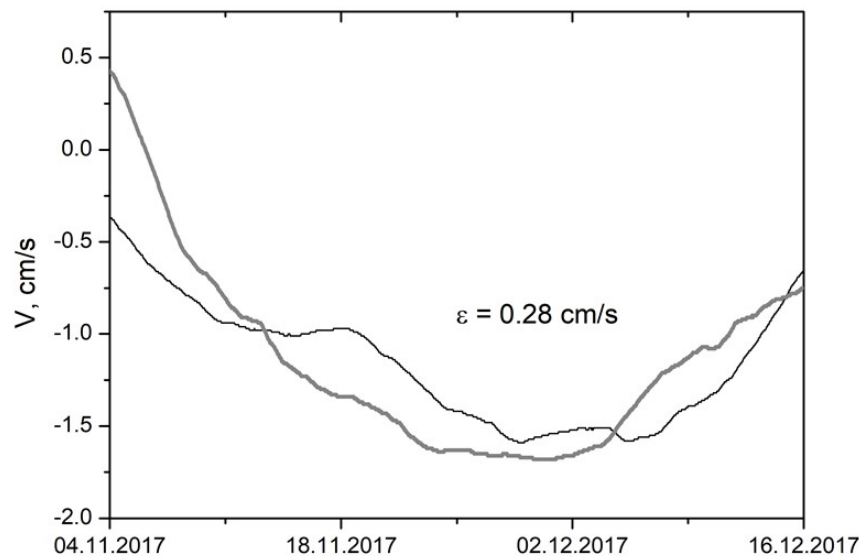**Figure 7.** Forecast of the flow velocity variation V (relative to the sliding 130-day average) with a fixed advancement of 39 days. The ε is the standard deviation of the forecasted (thin line) and factual (solid line) curves.

4. Conclusion and discussion

In the Baikal Experiment, a step has been taken to study the important property of macroscopic entanglement – the time-reversed response of the detector of nonlocal correlations to some natural processes with a large random component. The quantitative characteristics of macroscopic nonlocal correlations in reverse time are experimentally evaluated. The possibility of using these correlations to forecast random variations of the large-scale processes is demonstrated.

The quantum correlations in reverse time were observed in a number of modern experiments [13-17]. However, in all these experiments, theoretically much simpler microscopic systems were investigated and, more importantly, advanced correlations were detected after post-selection The latter allows to reach a perfect correlation, but excludes any possibility of its forecasting use. In Refs. [9,18] on a simple model of quantum teleportation it is shown that in experiment without

post-selection only partial extraction of quantum information is possible, therefore correlation is always imperfect (though it can be rather high in the macro-systems).

In our experiment we deal with nonlocal correlations of the macroscopic dissipative processes. In spite of recent great progress in awareness of constructive role of dissipation in macroscopic entanglement generation [19] and in development of macroscopic entanglement witnesses [20], strict theory of time reversal at macroscopic entangled states is absent yet. The experiments like ours are able to point out a framework for such a theory. On the other hand the (classically forbidden) possibility of random processes forecast is of obvious applied interest. In fact, this means the possibility of observation of the random future.

In conclusion, we cannot fail to note that for the first time the idea of the existence of symmetric retarded and advanced nonlocal correlations simultaneously with John. Cramer [1] was put forward (in different terms, but with the same result) by Nikolay Kozyrev [21]. Moreover, Kozyrev's experiments on measuring the responses of detectors to future positions of stars and other remote space objects anticipated and motivated our work in this area [22].

Acknowledgment

References

[1] Cramer J G 1980 *Phys. Rev.* D **22** 362
[2] Korotaev S M and Kiktenko E O 2015 *Physica Scripta* **90** 085101
[3] Hoyle F and Narlikar J V 1995 *Rev. Mod. Phys.* **67** 113
[4] Korotaev S M 2011 *Causality and Reversibility in Irreversible Time* (Irvine, CA: Scientific Research Publishing)
[5] Korotaev S M, Budnev N M, Serdyuk V O, Gorohov J V, Kiktenko E O, Zurbanov V L, Mirgazov R R, Buzin V B and Novysh A V 2013 *Physical Interpretations of Relativity Theory* ed V O Gladyshev, A N Morozov and P Rowlands (Moscow: BMSTU PH) pp 141-51
[6] Korotaev S M, Serdyuk V O, Kiktenko E O, Budnev N M and Gorohov J V 2015 *Unified Field Mechanics* ed R L Amoroso, L H Kauffman and P Rowlands (Singapore: World Scientific) pp 366–73
[7] Korotaev S M, Budnev N M and Serdyuk V O 2017 *J. Phys. Conf. Ser.* **918** 012003
[8] Korotaev S M, Serdyuk V O and Budnev N M 2018 *Unified Field Mechanics II: Formilations and Empirical Tests* ed R L Amoroso, L H Kauffman, P Rowlands and G Albertini (Singapore: World Scientific) pp 375–80
[9] Korotaev S M, Budnev N M, Serdyuk V O, Kiktenko E O, Gorohov J V and Zurbanov V L 2018 *J. Phys. Conf. Ser.* **1051** 012019
[10] Korotaev S M, Budnev N M Serdyuk V O, Zurbanov V L, Mirgazov R R, Shneer V S, Machinin V A, Kiktenko E O, Buzin V B and Panfilov A I 2015 *Geomagnetism and Aeronomy* **55** 398
[11] Korotaev S M, Budnev N M Serdyuk V O, Orekhova D A, Kruglyakov M S, Kiktenko E O, Mirgazov R R, Zurbanov V L, Gorohov J V, and Ryabov E V 2018 *Izvestia. Atmospheric and Oceanic Physics* **54** 1569
[12] Lean J L and Brueckner G E 1989 *Astrophys. J.* **337** 568
[13] Laforest M, Baugh J and Laflamme R 2006 *Phys. Rev.* A **73** 032323
[14] Lloyd S, Maccone L, Garcia-Patron R, Giovannetti V, Shikano Y, Pirandola S, Rozema L A, Darabi A, Soudagar Y, Shalm L K and Steinberg A M 2011 *Phys. Rev. Lett.* **106** 040403
[15] Ma X-S, Zotter S, Kofler J, Ursin R, Jennewien T, Brukner Č and Zeilinger A 2012 *Nature Physics* **8** 479
[16] Megidish E, Halevy A, Shacham T, Dvir T, Dovrat L and Eisenberg H S 2013 *Phys. Rev. Lett.* **110** 210403
[17] Danan A, Farfurnik D, Bar-Ad S and Vaidman L 2013 *Phys. Rev. Lett.* **111** 240402
[18] Kiktenko E O and Korotaev S M 2014 *Phys. Essays* **27** 548
[19] Kordas G, Wimberger S and Witthaut D 2012 *Europhys. Lett.* **100** 30007
[20] Amico L, Fazio R, Osterloch A and Vedral V 2008 *Rev. Mod. Phys.* **80** 517
[21] Kozyrev N A 1980 *Manifestation of Cosmic Factors on the Earth and Star* ed A A Efimov (Moscow: VAGO Press) pp 76-84 (in Russian)
[22] Kozyrev N A and Nasonov V V 1980 *Manifestation of Cosmic Factors on the Earth and Stars* ed A A Efimov (Moscow: VAGO Press) pp 85-93 (in Russian)