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Macroscopic entanglement and time reversal causality by data of the Baikal Experiment

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Abstract. Although the general theory macroscopic quantum entanglement is still in its infancy, consideration of the matter in the framework of action-at-a-distance electrodynamics predicted, for the random dissipative processes, observability of the advanced nonlocal correlations (time reversal causality). These correlations were really revealed in our previous experiments with some large-scale random heliogeophysical processes as the source ones and the lab detectors as the probe ones. However, the strongest macroscopic nonlocal correlations are observed at extremely low frequencies; therefore, the long-terms experiments therewith under very stable conditions, which are difficult to achieve in a usual laboratory, are necessary. To overcome this difficulty, a new experiment has been conducted on the base of Baikal Deep Sea Neutrino Observatory since 2012. Baikal thick water layer is an excellent shield against any local impacts on the detectors. The long-term series of measurements demonstrates that detector signals respond to the random global heliogeophysical processes, but this nonlocal causal connection proves to contain considerable time reversal component. Nonlocal nature of this connection is confirmed by violation of the steering inequality. In addition, advanced nonlocal correlation of the detector signal with a regional source-process – the random component of hydrological activity (macroturbulence) in the upper layer is revealed. The possibilities of the random processes forecast on nonlocal correlations are demonstrated.

1. Introduction

The general theory macroscopic quantum entanglement is still in its infancy, but consideration of the matter in the framework of action-at-a-distance electrodynamics [1] predicts for the random dissipative processes observability of the advanced nonlocal correlations through timelike interval (that is time reversal causality, which is allowed by the quantum principle of weak causality in the uncontrolled entangled states [2]). Moreover, action-at-a-distance electrodynamics predicts that the advanced component of nonlocal correlation can exceed the retarded one [3]. The propagation velocity for diffusion entanglement swapping through a medium can be very small. Accordingly, the retardation and advancement can be very large. Such correlations were revealed in our previous experiments with some large-scale random heliogeophysical processes as the source ones and the lab detectors as the probe ones [1].

To overcome difficulty with detector protection against long-period local impacts under usual laboratory conditions, a new experiment is conducting on the base of Baikal Deep Sea Neutrino Observatory [4-5]. Baikal thick water layer is an excellent shield against any local impacts on the detectors. The Baikal experiment aims, first, study of nonlocal correlations between the electrode detectors at different horizons in the lake and spaced at 4200 km one in the land laboratory, and second, study of correlations between the detector signals and large-scale natural dissipative processes with big random components. Data are processed by the methods of spectral, correlation and causal analysis. The several annual series of measurements, obtained since 2012, demonstrated that the detector signals respond to the main global source-process (which is, by data of all the previous lab experiment, the random component of solar activity and, to a lesser extent, of geomagnetic one). The causal connection of the detector signals is directed downwards: from the Earth surface to the Baikal floor. This nonlocal causal connection proved to contain considerable time reversal component, in all cases exceeding the retarded one. In addition, advanced nonlocal correlations of the detector signal with some regional source-processes were revealed. In particular, it was macroturbulence in the upper layer of the lake. The possibility of its forecast on nonlocal correlations was demonstrated. An important result was displaying of the advanced response of nonlocal correlation detector to the earthquake.

However, the fact that the main source-process is solar activity should be confirmed explicitly by data of a deep-sea detector. On the other hand, although the earthquakes are powerful and interesting events, they occur very seldom to obtain statistically reliable conclusions, therefore weaker, but continuous process of hydrological fluctuations is more convenient in this respect.

In the current paper we consider nonlocal correlations and phenomenon of time reversal causality with the main external global source-process (solar activity) and with an internal local source-process (macroturbulence in the upper Baikal layer), using the detector with the highest signal-to-noise ratio with respect to these processes. To prove nonlocal nature of advanced correlations by violation of steering inequality, we use also one more source: global geomagnetic activity. We demonstrate forecasting capability of the random processes on macroscopic nonlocal correlations.

2. Experiment and data

The Baikal deep-sea experimental setup is described in detail in Refs. [4] (primary configuration) and [25] (final configuration); so we present here only short description of the latter one.

The experimental setup is deployed in the Southwestern part of the lake. The site depth is 1367 m. The bottom detector *Ub* is set at the depth 1337 m, the top one *Ut* is set at the depth 47 m. For comparison, synchronous measurements with the detector on the Earth surface *Ul* (located in the laboratory in Troitsk spaced at 4200 km) are conducted. All the detectors are of electrode type, which by previous experience turned out the most reliable among other types (e.g. [1]). This type of detector is based on measuring of spontaneous variations of self-potentials of weakly polarized electrodes in the electrolyte (under suppressing of all classical local impacts). Every detector represents a couple of weakly polarized AgClAg electrodes HD-5.519.00 with practically zero separation. These electrodes are best in the World by their self-potential insensitivity to the environmental conditions.

The detector signals are measured and stored in the electronics unit set at the depth 20 m. The sampling rate is 10 s. The relative error of measurements is less than 0.01%. In addition, the electronics unit contains the temperature and acceleration sensors. The setup is fixed by the heavy anchor on the floor and by the submersed buoy at the depth 15 m. At a few kilometers from the setup, auxiliary measurements of the sea currents and magnetic field are conducted.

The deep-sea setup is designed to be operated autonomically for a year. Every March the electronic unit is lifted on the ice for data reading and battery changing and then it is installed again for the next year.

By some technical reasons, from 2015 the *Ub* detector channel ceased to withstand annual operation. But by previous data the detector *Ut* proved to be optimal for the signal-to-noise ratio in the study of external heliogeophysical processes (the greatest noise is contained in the detector on the Earth surface

Ul, the smallest – in the bottom one *Ub*, but in the latter the signal from the external processes have significantly shielded the water column). It stands to reason that *Ut* is optimal also in study of internal hydro-thermodynamic processes (macroturbulence), which occur practically only in rather thin upper layer of the Baikal Lake. Therefore, for the main purposes of current work we use data of the detector *Ut*.

According to entanglement monohamity principle a probe process in the detector can be entangled with only a few processes in the environment. Nonetheless, there is a problem of the correlation separation if (as in our case) the spectra of the different sources are overlapped. In addition, the larger space scale of the source, the larger expected advancement of macroscopic nonlocal correlation [1] and the longer time series is needed. For this reason, for study of correlation with solar activity in this work, we use biannual time series 2013/2015, when this activity was rather high, while for study of correlation with hydro-thermodynamic activity we use annual series (2016/2017), when solar one was almost minimal.

The macroscopic entanglement equation [1, 4] relates the entropy productions in the probe and source processes. In turn, the theory of the detector relates probe entropy variation with its signal. The same can easily be done for a simple source. However, since our source are not too simple, and not to contaminate the results by any model assumptions, we relate detector signal with source activity indexes qualitatively reflected the entropy variations. As the solar activity indexes we use the radio wave flux *R* at 2800 MHz and *X*-ray flux at 0.5 – 4 Å. The radio frequency 2800 MHz corresponds to emission from the level of maximal dissipation in the solar atmosphere (upper chromosphere – lower corona, where the magneto-sound waves dissipate). The *X*-rays emit approximately from the same level. As the index of macroturbulence, we use random long-period temperature fluctuations at the depth 20 m.

3. Data treatment

Data were processed by the methods of spectral, correlation and causal analysis. Although we consider quantum phenomena, in the experiment we deal with only classical output of measuring device and may use simpler classical version (just as in the experimental verification of Bell inequality using classical correlations or Shannon entropies).

Recall the essence of classical causal analysis. For any variables *X* and *Y*, in terms of Shannon marginal $S(X)$, $S(Y)$ and conditional $S(X|Y)$, $S(Y|X)$ entropies the independence functions can be defined:

$$i_{Y|X} = \frac{S(Y\,|\,X)}{S(Y)},\; i_{X|Y} = \frac{S(X\,|\,Y)}{S(X)},\; 0 \le i \le 1. \tag{1}$$

Roughly saying, the independence functions behave inversely to module of correlation one. However, they characterize one-way correlations, which are asymmetric for causally related variables. In addition, they are well suited for any linear and nonlinear relationships. Next, the causality function γ is considered:

$$\gamma = \frac{i_{Y|X}}{i_{X|Y}},\; 0 \le \gamma < \infty. \tag{2}$$

By definition *X* is the cause and *Y* is the effect if $\gamma < 1$. And inversely, *Y* is the cause and *X* is the effect if $\gamma > 1$. On theoretical and plenty of experimental examples, it had been shown that such a formal approach to causality did not contradict its intuitive understanding.

In terms of γ the principle of classical causality is formulated as follows:

$$\gamma < 1 \Rightarrow \tau > 0,\; \gamma > 1 \Rightarrow \tau < 0,\; \gamma \to 1 \Rightarrow \tau \to 0, \tag{3}$$

where τ is time shift of *Y* relative to *X*. Only in case of nonlocal correlation, one can observe violation of this principle. It is just the case of weak causality, which does not obey the combination of inequalities of axiom (3).

The strict dichotomy of the weak causality (violating chronology) and its counterpart, the strong one (respecting chronology), can be done only in the framework of quantum causal analysis, where another, more complicated measure of causality is used (the course of time c_2 instead of the causality function γ, because the latter loses sense at a negative conditional entropy) [1]. However, if both conditional entropies are non-negative, in particular for device classical output (even measuring an entangled state), both principles, the classical and strong causality are equivalent. Finite causality, which does not obey these principles, is weak causality. It may occur only in the entangled states. Thus violation of Ineqs. (3), say, $\gamma > 1$ at $\tau > 0$, is entanglement evidence that is a sufficient condition of nonlocality.
There is a way to test a wider sufficient condition of nonlocality in usual manner, not appealing to time shifts, as it is done through the violation of Bell-like and steering inequalities. Suppose some process C acts upon a distant process A by means of any local interaction along the causal chain $C \to B \to A$. The intermediate process B is situated so that local carriers of interaction cannot come A avoiding B (e.g. B occupies a spherical layer around A). Then the claim of locality implies the steering inequality (derived, e.g. in Ref. [1]):

$$i_{A|C} \geq \max\left(i_{A|B}, i_{B|C}\right). \tag{4}$$

Violation of Ineq. (4) is a sufficient condition of entanglement.

4. Results

The detailed study of nonlocal correlations between all three detectors: bottom one *Ub*, top one *Ut* and land (laboratory) one *Ul* was undertaken before during the year of almost maximal solar activity 2013/2014 [5]. The nonlocal causal connections of their signals proved to be directed downwards: *Ul*→*Ut*, *Ut*→*Ub*, *Ul*→*Ub*, but they contain the time reversal component, in all cases exceeding the retarded one. This excess depends on the mass of the absorbing medium separating the nonlocally correlating processes; the ratios of the maximal time reversal and time respecting (normal) causality functions reached 1.03, 1.12, 2.05 respectively.
Now we are concentrated on nonlocal correlation with solar (and partly geomagnetic) activity by data of biannual 2013/2015 time series with the detector *Ut*, optimal for the signal-to-noise ratio. The main source-process is solar activity. According to entanglement monogamy property, great nonlocal correlation with one subsystem implies only small correlations with other ones. Indeed, nonlocal correlations of detector signal with other natural (geophysical) random dissipative processes by data of all previous experiments turned out smaller. The dominance of solar activity is less in 2016/2017 series, we will confirm this fact below.
In Figure 1 the normalized amplitude spectra of the detector *Ut*, solar radio wave flux *R* (2800 MHz) and *X*-ray flux (0.5-4 Å) at the period range is from 10 to 460 days (d). As expected, *Ut* practically does not respond to deterministic variations of the solar activity, which is represent in *R* and *X* by split 27-day variation and its harmonics. Over longer periods, where the random component (in particular, the intermittent variation [6]) is dominated, the response in *Ut* is clearly visible. Detailed analysis showed the greatest similarity of the spectra of *Ut* with *R* in the band of periods 365>T>59 d, and with *X* in the band 365>*T*>77 d.
Next, to causal and correlation analysis data from such a band-pass filtration were used. The computation results are presented in Figures 2 and 3. Their stability was tested by alternate noising of the time series by the flicker noise (21% power).

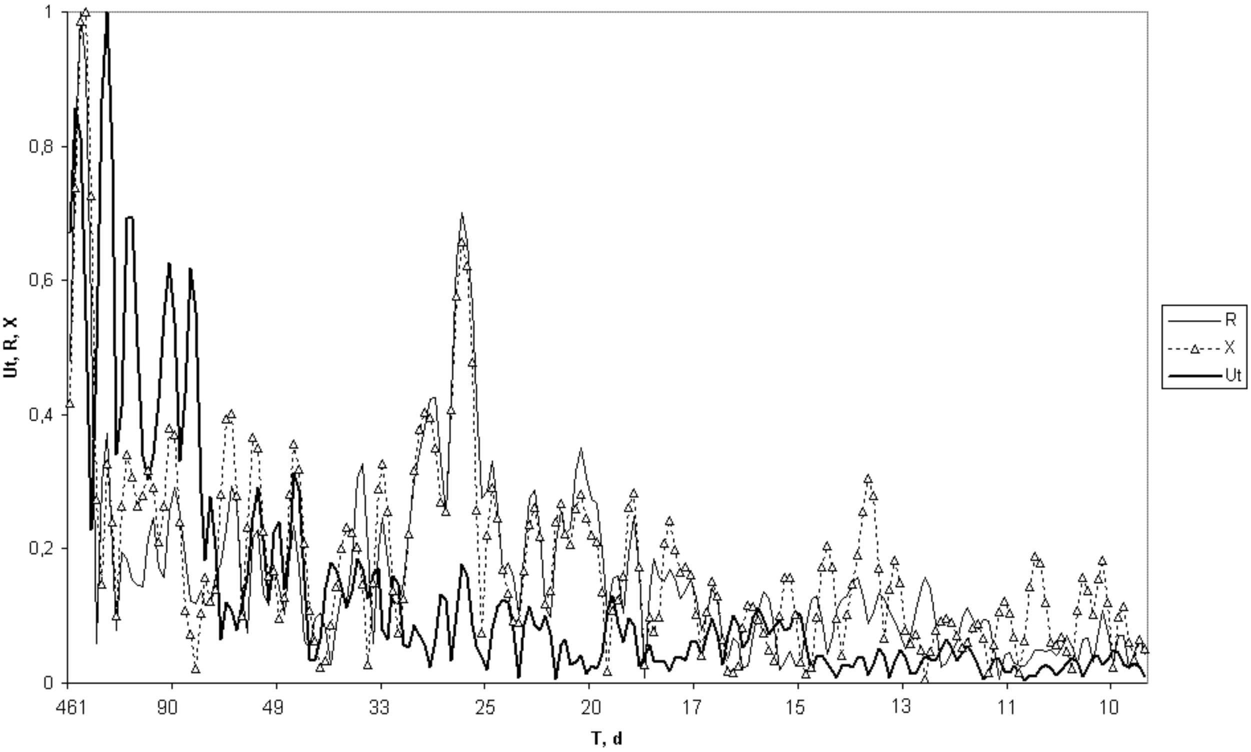

Figure 1. Normalized amplitude spectra of the signals of detector *Ut*, solar radio wave flux *R* and *X*-ray flux.

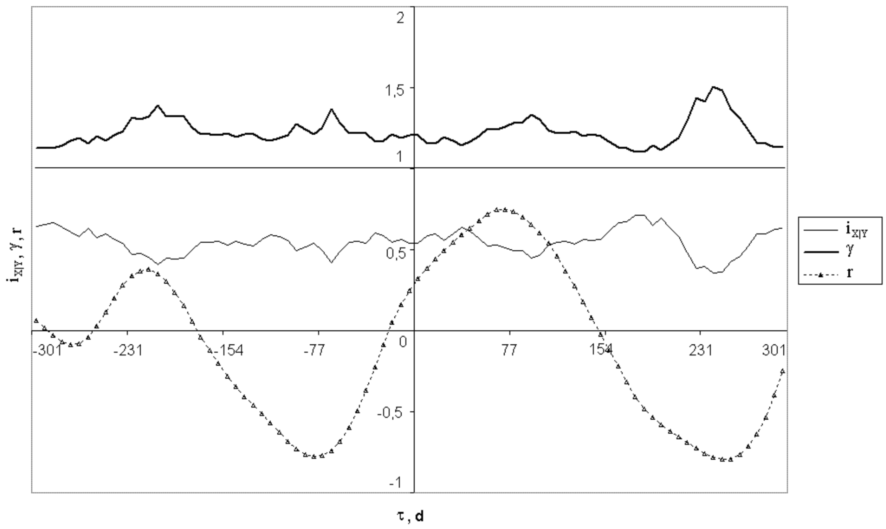

Figure 2. Causal and correlation analysis of *Ut* (X) and *R* (Y). τ < 0 corresponds to retardation of *Ut* relative to *R*, $\tau > 0$ – to advancement.

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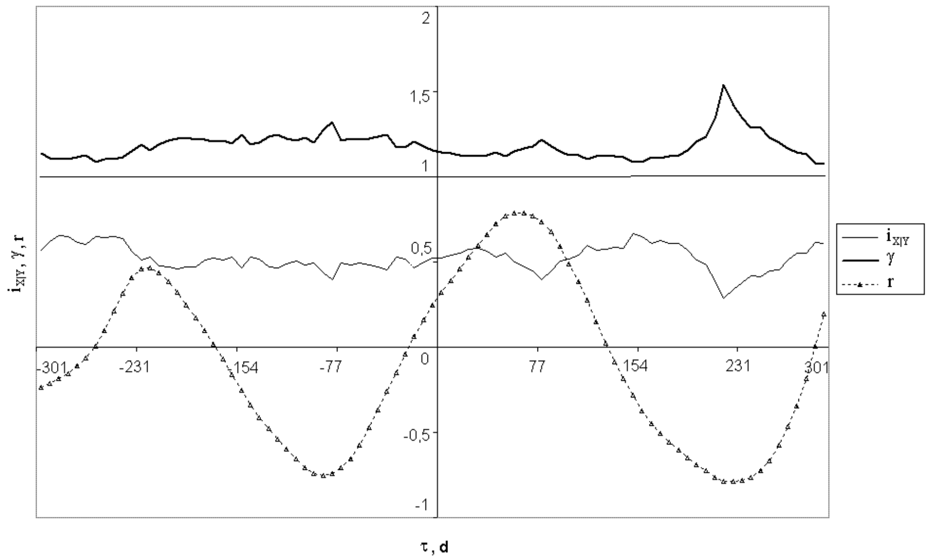

Figure 3. Causal and correlation analysis of *Ut* (X) and *X* (Y). τ < 0 corresponds to retardation of *Ut* relative to *X*, $\tau > 0$ – to advancement.

In a couple of *Ut* – *R* it is seen that solar activity is a cause with respect to detector signal ($\gamma > 1$) and the highest maximum of causality $\gamma = 1.5^{+0.0}_{-0.1}$ is observed at advancement of *Ut* with respect to *R* for 250 days. At the same advancement the deepest minimum of independence $i_{Ut|R} = 0.35^{+0.05}_{-0.00}$ and maximal correlation $r = -0.79^{+0.02}_{-0.01}$ are observed. In a couple of *Ut* – *X* the results are close: the extreme $\gamma = 1.5^{+0.1}_{-0.0}$, $i_{Ut|R} = 0.28^{+0.02}_{-0.00}$, $r = -0.79^{+0.02}_{-0.01}$ are at advancement 230 days. Thus, the characteristic for nonlocal connection of the random processes time reversal causality is observed.

The level of advanced correlation is sufficient to forecast solar activity with optimal advancement about 250 days. However, the large value of optimal advancement with dramatically reduced, due to the above-mentioned filtration, the length of *Ut* series make impossible yet to use forecasting algorithms based on computation of impulse transient response [1], or even simpler one based on sliding regression (as it was done in the similar problem in Ref. [5]), because they need long training interval. However, the very possibility of solar activity forecast is easily demonstrated by the series shift. It is shown in Figure 4 by the example of *R*.

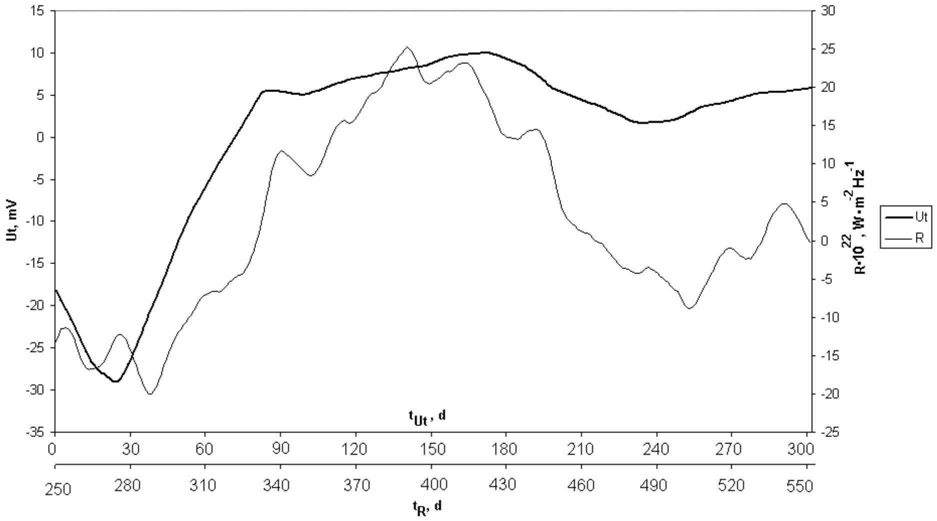

Figure 4. *Ut* approximately forecasts *R* with advancement 250 days.

In agreement with the results of all previous experiments of this kind, there is also a weaker advanced connection of the detector signal with the global geomagnetic activity characterized by the *Dst*-index. With filtration 365>*T*>59 days in the couple *Ut* – *Dst* at advancement of *Ut* with respect to *Dst* for 110 days the extreme values $\gamma = 1.3^{+0.0}_{-0.1}$, $i_{Ut|Dst} = 0.51^{+0.08}_{-0.00}$, $r = -0.65^{+0.01}_{-0.00}$ are observed; with filtration 365>*T*>77 days the extreme values are observed at the same advancement and amount to $\gamma = 1.2^{+0.1}_{-0.0}$, $i_{Ut|Dst} = 0.47^{+0.00}_{-0.01}$, $r = -0.68^{+0.03}_{-0.00}$. The smaller value of advancement compared to solar activity is also consistent with (observed in all previous experiments) a trend to a direct relation of this quantity with the scale of the source.

Although the nonlocal nature of the correlations follows from the observed violation of the principle of strong causality ($\gamma > 1$ at $\tau > 0$), the combination of connections of *Ut* with geomagnetic and solar activities presents the opportunity to another, independent proof of nonlocality, not appealing to time shifts, through violation of Ineq. (4).

In our case $A = Ut$, $B = Dst$, $C = R$ or X. Classical local influence of solar activity, indexed by *R* or *X* on geomagnetic one, indexed by Dst, is well known. However the electrode detector is insensitive to the local magnetic field (at least, up to 10^{-3} T), as well as it is insensitive to classical local impact of solar activity mediated by the cosmic ray flux [1]. However, even assuming that these ideas are incomplete and some classical correlations *R* or *X* with *Ut* are available, Ineq. (4) must be satisfied. Let us check it by substitution of experimental values of independence functions under the same filtration of the series $A = Ut$, $B = Dst$, $C = R$ or X.

For $C = R$ with filtration 365>*T*>59 days: $i_{Ut|R} = 0.35^{+0.05}_{-0.00}$, $i_{Ut|Dst} = 0.51^{+0.08}_{-0.00}$, $i_{Dst|R} = 0.57^{+0.00}_{-0.01}$; with filtration 365>*T*>77 days: $i_{Ut|R} = 0.34^{+0.00}_{-0.05}$, $i_{Ut|Dst} = 0.47^{+0.00}_{-0.01}$, $i_{Dst|R} = 0.54^{+0.00}_{-0.00}$. For $C = X$ with filtration 365>*T*>59 days: $i_{Ut|X} = 0.36^{+0.14}_{-0.00}$, $i_{Ut|Dst} = 0.51^{+0.08}_{-0.00}$, $i_{Dst|X} = 0.55^{+0.00}_{-0.00}$; with filtration 365>*T*>77 days: $i_{Ut|X} = 0.28^{+0.02}_{-0.00}$, $i_{Ut|Dst} = 0.47^{+0.00}_{-0.01}$, $i_{Dst|X} = 0.55^{+0.01}_{-0.01}$.

In all four variants Ineq. (4) is reliably violated. Thus, the nonlocal (quantum) nature of the observed in the Baikal experiment correlations is proved also through the violation of the steering inequality without resorting to arguments of time shifts.

Before to turn to analysis of the 2016/2017 series for study of detector correlation with internal (hydrological) processes, we note, that correlation with external (heliogeophysical) processes in spite of low solar activity certainly must remain. Consider the result of causal analysis of the detectors *Ut* and *Ul* (Figure 5) and compare it with the one obtained at high solar activity 2013/2014 [5]. In Figure 5 we observe $\gamma > 1$, that is there a causal connection *Ul*→*Ut* (as well as in 2013/2014); the highest maximum of causality $\gamma \approx 1.3$ and the deepest minimum of independence $i_{Ut|Ul} \approx 0.49$ are at advancement 24 days (1.4 and 0.34 respectively just at the same advancement in 2013/2014); the ratio of the maximal time reversal and time respecting (normal) causality functions is 1.02 (1.03 in 2013/2014). Causal connection remained similar, but weaker.

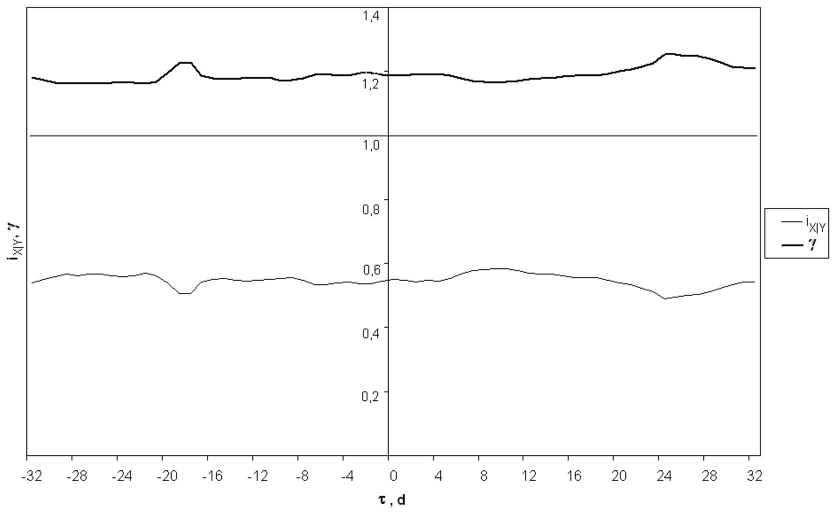

Figure 5. Causal analysis of *Ut* (X) and *Ul* (Y). $\tau < 0$ corresponds to retardation of *Ut* relative to *Ul*, $\tau > 0$ – to advancement.

In Figure 6 the amplitude spectra (in absolute units) of the detector *Ut* and temperature *t* in the active layer are presented. It is seen that at the long periods there is a certain similarity of the spectra *Ut* and *t*. Therewith their amplitude ratio proves to be much greater (of order 1 mV/K) than upper bound of a local influence (electrode temperature coefficient is 0.04 mV/K). It may be explained only by some nonlocal correlation.

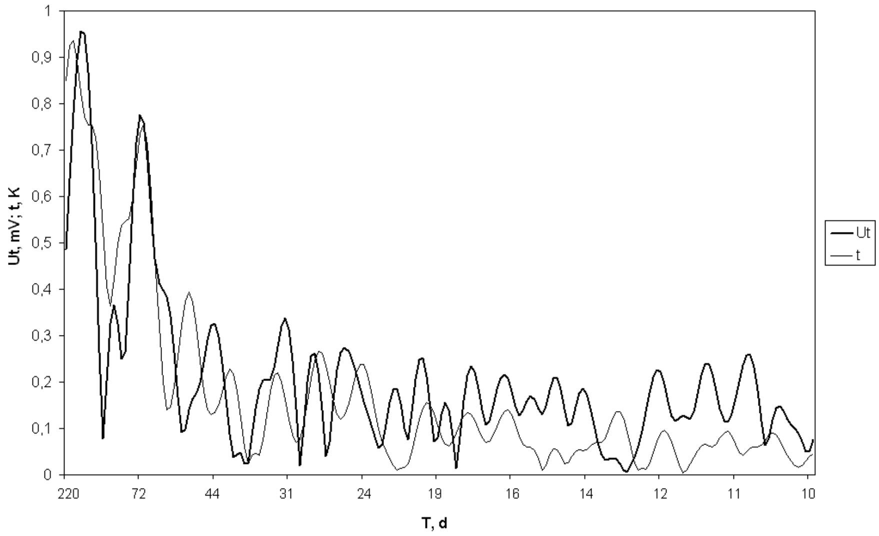

Figure 6. Amplitude spectra of the detector *Ut* (at horizon 47 m) and temperature *t* (at horizon 20 m).

Consider the results of causal and correlation analysis of *Ut* and *t* (Figure 7) with the broadband filtration, stemming from the spectra and corresponding to low-frequency macroturbulence, 156>*T*>48 days. $\gamma > 1$ that is *t* is a cause with respect to *Ut*, the advanced maxima of the causality function are greater than the retarded ones. We observe two, both advanced highest $\max\gamma = 1.5^{+0.1}_{-0.0}$, but only one of them, at τ = 25 days corresponds to the deepest $\min i_{Ut|t} = 0.19^{+0.1}_{-0.0}$ and the greatest value of correlation function $\max r = 0.99^{+0.00}_{-0.03}$. It is just manifestation of advanced nonlocal connection *t*→*Ut*.

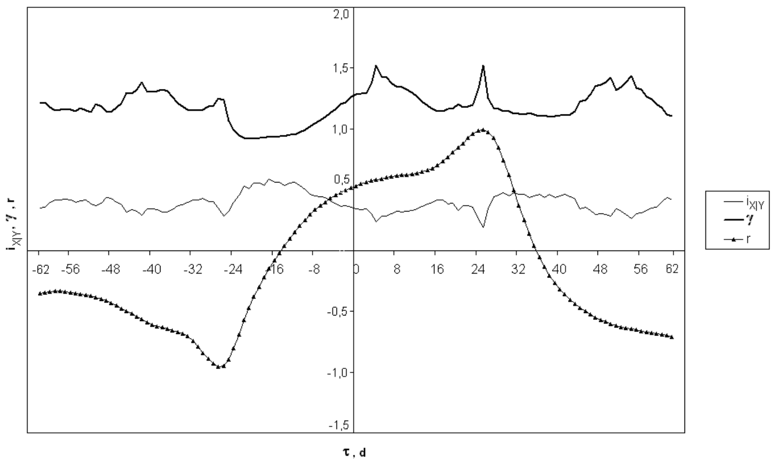

Figure 7. Causal and correlation analysis of U_t (*X*) and *t* (*Y*). $\tau < 0$ corresponds to retardation of U_t relative *t*, $\tau > 0$ – to advancement.

We can use both forecasting algorithms, mentioned above, to forecast the random temperature variation Δ*t* by the filtered signal of *Ut* with fixed advancement 25 days. However, the length of the possible forecasted Δ*t* series is short, because, first, band-pass filtering strongly shortens the length of *Ut* series and, second, the need for a primary training interval takes in given case at least 75-80 first days. In addition, with algorithm based on impulse transient response, third, the need of the solution regularization (postfiltering) shortens the length of forecasted Δt series again. Note also, that in any classical forecast, e.g. weather one, a forward problem is solved (computation of the effects by the causes). In contrast, we forecast the causes by the effects that are we solve, much more complicated inverse problem. Our purpose for now is only demonstration of a real forecast based on time reversal causality.

In the regression algorithm the regression coefficient on the training interval is computed, which then used for the computation of the first forecasted value. On the next step (hour), the training interval is moved forward, the procedure is repeated and the next value with the same advancement is forecasted, and so on. In the transient response algorithm [1] the long impulse transient response on the training interval is computed (by solving of the integral equation), which then is used, as its convolution with multitude of the preceding detector signal values, for the computation of the first forecasted value. Next, the procedure is repeated as well as in the former algorithm. Advantage of the latter one is taking into account non-Markovian nature of the process relation. Since the both methods are linear (although taking into account non-stationarity), the optimal advancement of forecasting is determined by the position of the main correlation function maximum.

The results are presented in Figure 8. The forecast on the sliding regression (Figure 8a), in spite of some unfit, demonstrates the mean accuracy acceptable for the practical purposes. The forecast series on the sliding impulse transient response (Figure 8b) is short to look impressive, but its mean accuracy is much better, as it was expected.

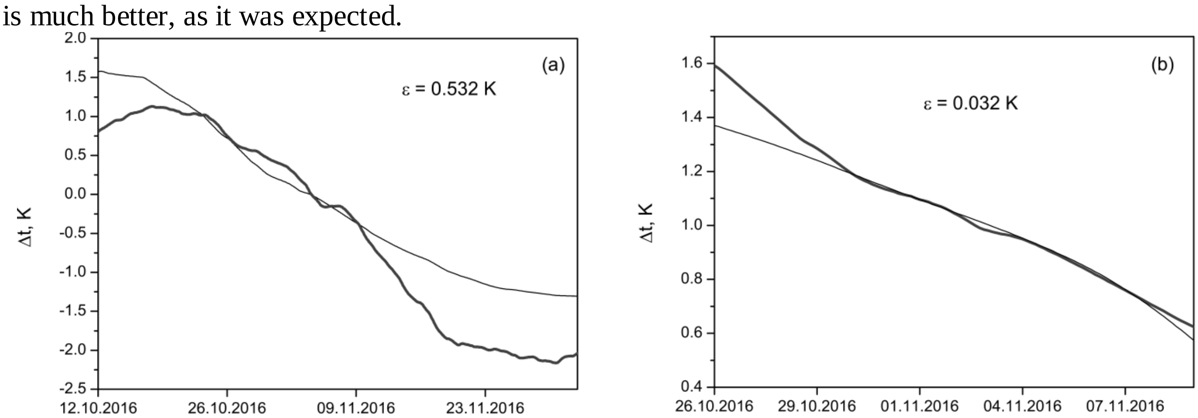

Figure 8. Forecast of the temperature variation Δt with fixed advancement 25 days by the method of sliding regression (a) and by the method of sliding impulse transient response (b). The ε is the standard deviation of the forecasted (solid line) and factual (thin line) curves.

5. Conclusion and discussion

The Baikal experiment has revealed a prominent property of macroscopic entanglement – the advanced response of nonlocal correlation detector to some natural processes with big random component. Such time reversal causality can be even use for the random process forecast.

Various researchers independently [2, 7-9] suggested the idea about quantum information propagation backward in time. This idea has been confirmed by observations of advanced nonlocal correlations in the experiments with low-dimensional systems (including a few particles) [8-11]. In these experiments, the advanced correlations were revealed *post factum*, in agreement with common view that quantum information can be decoded only with ancillary classical one, propagating forward in time. However, the latter is true if we aim to get decoded quantum information from the future (*a posteriory*) with unit probability. If we aim to get such information with finite probability, it becomes possible without ancillary classical channel [12]. It can be illustrated by the simplest example of qubit teleportation protocol, where Bob do not use classical communication with Alice, but instead measure state of his particle (one from the entangled pair emitted by EPR-source) with result $|0\rangle_B$ or $|1\rangle_B$. Suppose Alice teleports a definite state $|0\rangle$. Performing its joint measurement with her particle from the entangled pair, she obtain randomly one of four results (Bell states) $\left|\Psi^{\pm}\right\rangle_A$, $\left|\Phi^{\pm}\right\rangle_A$, and one can guess which one with probability 1/4. The joint three-particle state at any moment of Bob measurement, including a moment before (!) Alice measurement (Bob can be closer to the source than Alice) is $1/2\left(-\left|\Psi^{-}\right\rangle_A\left|1\right\rangle_B+\left|\Psi^{+}\right\rangle_A\left|1\right\rangle_B+\left|\Phi^{-}\right\rangle_A\left|0\right\rangle_B-\left|\Phi^{+}\right\rangle_A\left|0\right\rangle_B\right)$. Hence, Bob can guess Alice result with probability 1/2. The probability of his successful forecast is twice higher as compared to random guess. Physically, such a possibility to observe the random future is explained in this example by propagation of quantum information backward in time from Alice setup to EPR-source [2, 7-9].

Quantum information by itself can only partly be decoded. Therefore, the forecast of the random processes on nonlocal correlations is doomed to be probabilistic. However, for high-dimensional (macroscopic) system the probability of success can be much greater than in above qubit example. On the other hand, owing to decoherence, the entanglement degree of the macroscopic states is unavoidable very low and that prevents the success. Most of contemporary experimental studies of macroscopic entanglement (e.g. [13-14]) does not concern time problem yet. Our investigation was inspired by the prominent experimental results of Nikolay Kozyrev who was the first to discover advanced nonlocal correlations on interstellar scale, although he interpreted them in semiclassical terms [15].

The problem of time reversal propagation of quantum is associated with the problem of closed timelike curves (CTC). David Deutsch in his seminal work [16] stressed that his quantum-mechanical proof of the time travel possibility along CTC is applicable without any change to a macroscopic body. CTCs can exist not only in the curved space-time of the wormholes, but also in the flat space-time with some quantum circuits, although their properties are rather different [17]. Self-consistency of CTC allows a probabilistic forecast of the random future, as in our case.

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