Advanced response of Baikal macroscopic nonlocal correlation detector to solar activity

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Abstract. The long-term Baikal Deep-Sea Experiment on study of macroscopic entanglement and advanced response of nonlocal correlation detectors to natural random dissipative processes is conducting. There are both advanced and retarded nonlocal correlations, which correspond to the same direction of causality. However, time reversal causality prevails over usual time respecting one. It is the most prominent property of macroscopic entanglement and manifestation of quantum principle of weak causality. In particular, there is an advanced response to the random component of solar activity, which can be used for the forecast of this component.

1. Background

Macroscopic quantum entanglement is phenomenon studied in some special cases only; its consistent theory is not developed yet. However, the heuristic equation of macroscopic entanglement was suggested [1], according to which the processes prove to be correlated with symmetric retardation and advancement. For diffusion entanglement swapping the retardation and advancement can be large. The symmetry of the retarded and advanced correlation components is broken by a shielding medium, suppressing the retarded component in a greater extent. The advanced correlation meets the quantum principle of weak causality: for the uncontrolled entangled states advanced nonlocal correlations through a timelike interval and hence time reversal causality are possible. As the causes in these states are the random processes, such a time reversal causality does not imply the well-known classical paradoxes. It was experimentally demonstrated in the low-dimensional quantum systems [2-5].

In the previous experiments (reviewed in Ref. [1]) macroscopic nonlocal correlations of the probe processes in the detectors (providing their isolation from any classical local impacts) with some natural large-scale dissipative processes with big random component. Solar activity proved to be the dominant source-process. The most important results were detection of advanced nonlocal correlations and experimental proof of time reversal causality for the random processes. The mathematical tool for this proof is causal analysis. It is based on definition for any variables \(X\) and \(Y\), via Shannon entropies \(S\), the independence functions \(i_{i|X} = S(Y|X)/S(Y), i_{X|Y} = S(X|Y)/S(X), 0 \leq i \leq 1\) and causality function \(\gamma = i_{i|X}/i_{X|Y}, 0 \leq \gamma < \infty\). 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 $\gamma > 1$. If $\tau$ is time shift of $Y$ relative to $X$, then the principle of classical causality is formulated as follows: $\gamma < 1 \Rightarrow \tau > 0$, $\gamma > 1 \Rightarrow \tau < 0$, $\gamma \rightarrow 1 \Rightarrow \tau \rightarrow 0$. Only in case of nonlocal correlation, one can observe violation of these inequalities. Such a violation allowed to forecast the random components of solar and geomagnetic activity [6].

Since macroscopic nonlocal correlations manifest themselves at extremely low frequencies, for their detection the long-terms experiments with the maintenance of highly stable conditions in detectors are necessary. This is implemented under the conditions of the Baikal deep-sea experiment, which has already brought a number of important results on correlations with large-scale geophysical processes [7]. The experimental setup includes three electrode detector of macroscopic nonlocal correlations: $Ub$ and $Ut$ at depths of 50 m and 1300 m respectively, and remote at 4200 km land detector $Ul$. The detector $Ut$ has the maximal signal-to-noise ratio with respect to external heliogeophysical processes.

2. **Response of a macroscopic correlation detector to solar activity**

Below we analyze the response of $Ut$ detector signal to heliogeophysical processes by data of the first continuous two-year measurement series (2013/2015). The detector $Ut$ turned out optimal for the signal-to-noise ratio in the study of these 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).

In Figure 1 the normalized amplitude spectra of the detector $Ut$, solar radio wave flux $R$ (at 2800 MHz) and $X$-ray flux (at 0.5-4 Å) at the period $T$ range is from 10 to 461 days are shown. As was to be expected $Ut$ practically does not respond to deterministic component of solar activity variations, which is represented in $R$ and $X$ by split 27-day variation and its harmonics. Over longer periods, where the random component of solar activity is dominates, 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 $365 > T > 59$ days, and with $X$ in the band $365 > T > 77$ days. Next to causal and correlation analysis data from such band-pass filtration were used.

![Figure 1](image_url). Normalized amplitude spectra of detector signal $Ut$, solar radio wave flux $R$ and $X$-ray flux.
The causal and correlation 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). As one can see \( \gamma > 1 \), i.e. \( Ut \) is an effect of \( R, X \) at any \( \tau \). In a couple of \( Ut-R \) 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 \( i_{U\tau|R} = 0.35^{+0.05}_{-0.00} \) and maximal correlation \( r = -0.79^{+0.02}_{-0.01} \) are observed. In a couple of \( Ut-X \) the results are close: the extreme \( \gamma = 1.5^{+0.1}_{-0.0} \), \( i_{U\tau|R} = 0.28^{+0.02}_{-0.00} \), \( r = -0.79^{+0.02}_{-0.01} \) are at advancement 230 days.

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

**Figure 3.** Causal and correlation analysis of \( Ut \) (X) and \( X \) (Y). \( \tau<0 \) corresponds to retardation of \( Ut \) relative to \( X \), \( \tau>0 \) – to advancement.
The level of advanced correlation is sufficient to forecast solar activity with advancement about 250 days. However, the length of the series $U_t$ so far is insufficient to apply the effective forecasting algorithm [6]. But the very possibility of solar activity forecast is easily demonstrated by the series shift. It is shown in Figure 4 by the example of $R$.

![Graph](image)

**Figure 4.** $U_t$ approximately forecasts $R$ with advancement 250 days.

In agreement with the results of all previous experiments of such a kind [1], there is also a weaker advanced connection of the detector signal with the global geomagnetic activity characterized by the $Dst$-index (this index stresses a random component of the process). With filtration $365>T>59$ days in the couple $U_t$- $Dst$ at advancement of $U_t$ with respect to $Dst$ for 110 days the extreme values $\gamma = 1.3^{+0.1}_{-0.0}, i_{U_t|Dst} = 0.51^{+0.08}_{-0.00}, r = -0.65^{+0.01}_{-0.00}$ are observed; with filtration $365>T>77$ days extreme values are observed at the same advancement and amount to $\gamma = 1.2^{+0.1}_{-0.0}, i_{U_t|Dst} = 0.47^{+0.00}_{-0.01}, r = -0.68^{+0.03}_{-0.00}$.

3. Verification of nonlocal nature of correlations

The observed violation of the principle of strong (classical) causality described above is a sufficient condition of nonlocality. However, taking into consideration the singularity of this entanglement evidence, let us now verify a necessary condition of nonlocality and besides do it in more traditional manner not appealing to time shifts (as this is done through violation of Bell-like inequalities and steering inequalities). We are interested in a steering inequality, because it is just appropriate necessary condition of locality. The combination of connections of $U_t$ with geomagnetic and solar activities provides an opportunity for this.

Suppose some process $C$ acts upon a distant process $A$ by means of any local interaction along the causal chain $C \rightarrow B \rightarrow A$. 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]):

$$i_{A|C} \geq \max \{ i_{A|B}, i_{B|C} \}$$  \hspace{1cm} (1)
In our case $A = Ut$, $B = Dst$, $C = R$ or $X$. Note, classical local influence of solar activity, indexed by $R$ or $X$ on geomagnetic activity, indexed by $Dst$, is well known. Let us verify Ineq. (1) by substitution of experimental values of independence functions under the same filtration of the series $A = Ut$, $B = Dst$, $C = R$ or $X$.

With filtration $365 > T > 59$ days: for $C = R$: $i_{U|R} = 0.35^{+0.05}_{-0.00}$, $i_{U|D} = 0.51^{+0.08}_{-0.00}$, $i_{D|R} = 0.57^{+0.00}_{-0.01}$; for $C = X$: $i_{U|X} = 0.36^{+0.14}_{-0.00}$, $i_{U|D} = 0.51^{+0.08}_{-0.00}$, $i_{D|X} = 0.55^{+0.00}_{-0.00}$. With filtration $365 > T > 77$ days: for $C = R$: $i_{U|R} = 0.34^{+0.00}_{-0.00}$, $i_{U|D} = 0.47^{+0.00}_{-0.01}$, $i_{D|R} = 0.54^{+0.00}_{-0.00}$; for $C = X$: $i_{U|X} = 0.28^{+0.02}_{-0.00}$, $i_{U|D} = 0.47^{+0.00}_{-0.01}$, $i_{D|X} = 0.55^{+0.01}_{-0.01}$. In all four variants Ineq. (1) is reliably violated.

Thus, the nonlocal nature of the observed in the Baikal experiment correlations between the detector signal and solar activity is verified through the violation of the steering inequality without resorting to time relations.

4. Conclusion

Advanced response of Baikal macroscopic nonlocal correlation detector to solar activity has been revealed. This remarkable manifestation of quantum principle of weak causality can be used for the forecast of random component of solar activity. Nonlocal nature of the observed correlations has also been confirmed by violation of the steering inequality.

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