A search for gamma-ray counterparts to gravitational wave events in Konus-Wind data

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Abstract. The recent discoveries in multi-messenger astronomy allow us to study the Universe in a new way. The Advanced LIGO and Advanced Virgo gravitational-wave (GW) detectors have opened the possibility for regular detection of transients from compact binary merger events. The Konus-Wind (KW) spectrometer continuously observes the whole sky and enables searches for transient events over various timescales from milliseconds to hours. It provides a unique opportunity to study high energy transients, in particular, gamma-ray counterparts to gravitational wave detections. In this paper, we present the methodology and results of the search for gamma-ray counterparts to 56 GW events in KW data. While no counterpart candidate was found in our search, we report upper limits on soft gamma-ray emission from these events, including several events not observed by other wide-field high-energy instruments such as Fermi-GBM, INTEGRAL-SPI-ACS and Swift-BAT. We finally discuss the potential of KW to detect bursts as weak as GRB 170817A.

1. Introduction
The first direct detection of gravitational waves [1] started a new era in fundamental physics and observational astronomy. During three observing runs (O1/O2/O3), from 2015 September to 2020 March, the advanced LIGO and Virgo detected 65 GW events. Most of these were associated with binary black holes (BBH), and only two were reliably identified with a neutron star - neutron star (BNS) merger: GW170817/GRB 170817A and S190425z [2, 3]. A more detailed GW detection statistics is shown in Figure 1.

GW170817 is, so far, the sole event accompanied by electromagnetic (EM) radiation. A weak short gamma-ray burst, designated GRB 170817A, was detected by Fermi-GBM [4] and INTEGRAL-SPI-ACS [5] at approximately ~ 1.7 s offset to the merger time. This joint gravitational and EM detection provided the first direct evidence to confirm a long-standing hypothesis that short GRBs are caused by neutron star mergers. The subsequent extensive follow-up campaign allowed the detection of the optical transient and later the afterglow spanning all bands of EM spectrum [6, 7, 8, 9, 10].

The identification and study of EM, in particular gamma-ray, counterparts to GW events is important as it allows us to gain a further insight on the source properties, to probe its environments and to investigate the formation and evolution of compact objects. However, searching for EM counterparts is challenging because their luminosity expected to decay rapidly, and localization regions of GW events provided by LIGO/Virgo are currently up to thousands of square degrees, so a part of the region may be occulted by the Earth to low-Earth orbit observatories such as Fermi and Swift. Besides that, these observatories are usually switched...
Fermi-GBM, INTEGRAL, and Swift-BAT observations of GW Events during O3

75% 14% 7% 4%
not observed by three instrument
not observed by two instrument
not observed by one instrument
observed

Possible Sources of GW Events with classification probability > 85%

Figure 1. GW event statistics. Left: Source classification over O1/O2/O3 observing runs. The category ”MassGap” means compact binary systems with at least one compact object whose mass is in the hypothetical mass gap between neutron stars and black holes (3-5 solar masses). There are also S200114f with no source classification and six events with a lower values of source classification probability (4 BNS and 2 NSBH candidates). Right: Fermi-GBM, INTEGRAL-SPI-ACS and Swift-BAT observation overview during O3 run. All events were observed by KW.

off during the South Atlantic Anomaly passages. Thus, full-sky monitoring instruments are expected to play an important role in searches for EM counterparts to GW events, such as INTEGRAL-SPI-ACS and Konus-Wind.

Konus-Wind (KW) [11], running successfully since 1994, is a scintillation gamma-ray spectrometer, which consists of two identical NaI (Tl) detectors. It was developed at the Ioffe Institute and mounted on board Wind spacecraft (NASA), which is currently in a Lissajous orbit at the $L_1$ libration point of the Sun-Earth system. The experiment has a unique set of properties which make it a powerful tool to study hard X-ray/soft gamma-ray transients, particularly in multi-messenger context: stable background, continuous coverage of the full sky, high temporal resolution, and the wide (20 keV–15 MeV) energy range of spectral measurements. The instrument has two operational modes: waiting (continuous) and triggered. The continuous waiting-mode data allows searches for sources too weak to trigger KW. In this mode, count rates are recorded in three energy windows G1 (20 - 80 keV), G2 (80 - 320 keV), and G3 (320 - 1300 keV) with 2.944 s time resolution.

In this paper, we present methodology and results of the search in KW data for gamma-ray counterparts to 56 GW events detected during the O3 run. In Section 2, we briefly describe our technique of the EM counterpart search and upper limit calculations for individual events, estimate the KW upper limits, and perform a stacked analysis of the KW observations of all 56 events. In Section 3 we summarise the results and conclude.

2. Analysis technique

Appearance of the EM signal in the form of a short gamma-ray burst accompanying GW from the merge of BNS (and NSBH) systems has been predicted more than 30 years ago [12][13][14]. In certain cases, core collapse events that lead to long GRBs may emit a strong enough GW signal
to be detected by LIGO/Virgo GW detectors [15]. BBH mergers are not typically expected to be accompanied with EM radiation [16]. However, several scenarios were proposed in which, under certain circumstances, BBH mergers may be able to produce EM radiation [17, 18, 19]. The time window used for GW-EM coincidence search is determined by the expected delay between the GW signal and the GRB, which ranges from 10 ms to a few seconds for short GRBs and at least $\sim 10$ s for long GRBs [20].

2.1. Search and upper limit calculations
To search for EM emission from GW events, we first estimate the background by applying a linear fit to the KW count rate using data from two time intervals: $(T_0 - 1000 \text{ s}, T_0 - 100 \text{ s})$ and $(T_0 + 100 \text{ s}, T_0 + 1000 \text{ s})$ relative to the time $T_0$ of the GW event trigger. Then we search for significant ($> 5\sigma$) excess over the background in the time interval $T_0 \pm 100$ s. The search is performed in each detector (S1 and S2) and six energy channel combinations (G1, G2, G3, G1+G2, G2+G3 and G1+G2+G3), on temporal scales from 2.944 s to 100 s [21]. While no counterpart candidate was found in our search, we estimate upper limits on the presence of soft gamma-ray transient, which allow to constrain an energetics of possible accompanying GRB (long or short).

For upper limit calculations we use data from the KW detectors according to the ecliptic latitude of GW localization region. For a localization spanning both ecliptical hemispheres, we select the least constraining upper limit from both detector data and assuming the 90 degree incident angle. For any type of the GW event we estimate two upper limits. For a possible short burst lasting less than 2.944 s and having a typical KW short GRB spectrum (an exponentially cut off power law with $\alpha = -0.5$ and $E_p = 500$ keV [22]) we provide a limit on the 20–1500 keV fluence. For a typical long GRB spectrum (the Band function with $\alpha = -1$, $\beta = -2.5$, and $E_p = 300$ keV) we derive a limiting peak flux (20–1500 keV, 2.944 s scale).

Dependence of an upper limit on the source location and the spectral shape assumption is accounted for through the count-to-energy conversion factor $k$, which is used to convert upper limit on the source counts to energy flux or fluence upper limits (see details of upper limits calculation in [23]). We show this dependence in Figure 2 for two model spectra described above.

2.2. Modeling
In order to estimate the typical upper limit values, that KW is able to provide given the source location and background count rate, we performed the following simulations.

For each simulation run, we sample an incident angle $i$ from a distribution with pdf

$$f(i) = \begin{cases} 
0, & i < 0 \\
\sin i, & 0 \leq i \leq \pi/2 \\
0, & i > \pi/2
\end{cases}$$

and extract background levels in channels (G1, G2, G3) from real KW data at a time randomly selected in the O3 time span. Then we generate 68 points (200 s/2.944 s) of simulated data for each energy channel from the Poisson distribution with average background level in the corresponding energy channel. We then use the generated datasets and incident angles to compute upper limits on fluence and peak flux, in the same way as described above. The whole procedure is repeated independently for each detector. Figure 3 shows the upper limit distribution obtained with 10000 simulated datasets and the upper limit distributions derived for GW events during O3 run from the KW data. The notable difference between two distributions is due to different incident angle strategy used in upper limits calculations: to account for large size of GW localization region, for the majority of GW events we assumed incident angle of
Figure 2. Dependence of the count-to-energy conversion factor on source incident angle for two model spectra (CPL with $\alpha = -0.5$ and $E_p = 500$ keV; Band function with $\alpha = -1$, $\beta = -2.5$, and $E_p = 300$ keV) for S1 (left) and S2 (right) detectors. The Y-axis represents the count-to-energy conversion factor $k$ normalized by factor $k_0$, obtained for incident angle of 0 degrees.

90 degrees, and hence the corresponding upper limit distributions are skewed towards more conservative, higher values (see Figure 2). In 95% of cases, KW is able to provide upper limits for individual events of $(4.4–9.4) \times 10^{-7}$ erg cm$^{-2}$ on fluence of a possible short GRBs and of $(1.2–2.6) \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ on peak flux of long GRBs.

Figure 3. Distribution of upper limits on the 20–1500 keV fluence for short burst lasting less than 2.944 s (left) and on peak flux for long burst (right) derived from simulated datasets. Mean and 95% confidence interval are shown by dashed black and red lines, respectively. Distribution of upper limits derived from KW data is shown by stepped black line.
2.3. Stacked Analysis
We performed a stacked analysis of the KW observations of all 56 GW events during O3 run. The KW light curves and background levels to be summed were each centered on a bin comprising the candidate GW trigger time. We found no statistically significant excess of emission over background level within the stacked sample. The upper limits derived from the stacked data show up to a factor of eight improvement on the individual upper limits presented in Figure 4. We estimate it to $1.3 \times 10^{-7}$ erg cm$^{-2}$ on the 20–1500 keV fluence for a short burst lasting less than 2.944 s and to $3.3 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ on the peak flux of a long burst.

3. Results and conclusions
Using the approach described in the previous section, we derived upper limits on EM fluence/peak flux and estimate intrinsic luminosity for all 56 GW events discovered during O3 observational run assuming the median luminosity distance from the GW detection [3]. The results are shown in Figure 4.

In this paper, we introduced our strategy to search for soft gamma-ray counterparts to GW binary coalescence events in the waiting mode KW data. We described the methodology we use to calculate upper limits on possible emission and reported results on all O3 GW events with individual and stacked analysis. The obtained individual upper limits are $(5–11) \times 10^{-7}$ erg cm$^{-2}$ for short GRBs and $(1–3) \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ for long bursts. The stacked data analysis allows us to set up to a factor of eight more stringent than individual upper limits. While differences in energy bands and assumed spectral models made a direct comparison of upper limits provided
by different instruments difficult, they are typically around a few $10^{-7}$ erg cm$^{-2}$ s$^{-1}$ (see GCN
Circulars, e.g. [24, 25, 26]), the same order of magnitude as KW.

Using the short GRB sample from Fermi-GBM GRB catalog [27] we find that the minimum
short GRB fluence (10-1000 keV) required to produce a 4 $\sigma$ excess over background in the KW
waiting-mode data is $\gtrsim 3.5 \times 10^{-7}$ erg cm$^{-2}$. GRB 170817A, which is, so far, the only detected
GW counterpart had a fluence of $1.8 \pm 0.4 \times 10^{-7}$ erg cm$^{-2}$ [4]. Thus, KW, which is able to detect,
with nearly 100% duty cycle, events just a factor of two more bright (in the observer frame)
that GRB 170817A, continues to provide an important tool for multi-messenger astronomy.

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