Search and Observations of Optical Counterparts for Events Registered by LIGO/Virgo Gravitational Wave Detectors

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Abstract. The problem of search for optical counterpart of LIGO/Virgo events are discussing. Multi-messenger astronomy boosts the use a huge amount of astronomical data obtained by virtually all observatories around the world. We are discussing different methods used for observations, problem of search for transients in the extremely large localization error-box of LIGO/Virgo events, and lessons obtained during second observational run of LIGO/Virgo in 2017. In particular we present our experience and results of follow up observations of LIGO/Virgo optical counterpart candidates.

Keywords: Multi-messenger astronomy, gravitational waves, LIGO/Virgo, gamma-ray bursts, afterglow, kilonova, photometry.

1 Introduction

The problem of search and observations of new transient objects is one of the main problems in modern astrophysics. It requires wide-field observations with some initial all-sky catalogue of stationary sources for comparison. Dedicated surveys and experi-

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ments produce huge amounts of data daily in every domain of electromagnetic spectrum: in high energy range [1], optics [2, 3], and radio [4], as well as in cosmic particles window [5] and gravitational waves [6]. The surveys of new generation, like Large Synoptic Survey Telescope [7], will produce data of unprecedented volume and complexity. Reduction and analysis of these enormous data sets is already out of human's capacity and is similar to a search of a needle in a haystack. This problem is also connected to the search of transients related to the gravitational waves detections in very large localization areas, provided by LIGO and Virgo observations during theirs third scientific observational run in 2019.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is designed to open the field of gravitational-wave astrophysics through the direct detection of gravitational waves predicted by Einstein's General Theory of Relativity [8]. LIGO's multi-kilometer-scale gravitational wave detectors use laser interferometry to measure the minute ripples in space-time caused by passing gravitational waves from cataclysmic cosmic events such as merging neutron stars (NSs) or black holes (BHs), or by supernovae. LIGO consists of two widely separated interferometers within the United States – one in Hanford, Washington and the other in Livingston, Louisiana – operated in unison to detect gravitational waves.

The first success of LIGO observations came in 2015 with the first direct observations of gravitational waves from the binary black hole merging GW150914 [9]. In 2017, when the sensitivity of LIGO detectors increased, and Virgo detector in Italy started its first observational cycle [10], the merging of binary neutron star was detected for the first time [11].

In the context of gravitational waves detection, the most important problem for astrophysics is the search, identification, and observations of the possible electromagnetic (EM) counterpart of the event. The General Relativity predicts no EM radiation from the binary BH coalescence since, in theory, there is no enough matter outer the source that can produce it. In practice, there may be some radiation caused by accretion of a circumstellar matter on the resulting black hole, but its predicted flux is extremely low (e.g. [12]). Quite different situation is the binary NS merging (BNS). In this case, the merging objects consist of an ordinary matter that may produce high-energy EM radiation process (short gamma-ray burst) after the merging BNS an afterglow of wide energy range, and most interesting BSN counterpart which is called 'kilonova'.

The association between BNS merging, short gamma-ray bursts and kilonovae was first predicted theoretically [13], and then was confirmed observationally with the detection of GW170817/ GRB 170817A / AT2017gfo [14]. Besides the fact that GW170817 was the first case of the registration of gravitational waves from a BNS merging, it was also the first detection of gravitational waves and EM radiation from the same source [15].

A signal from the binary system merging is modeled numerically based on the Einstein's General Theory of Relativity and represents a package of oscillations increasing in amplitude with a decreasing period. The processing algorithm of LIGO and Virgo detectors searches for modeled templates in the received data using wavelet analysis. Localization on the sky is performed by triangulation method, measuring the time lag between the detection time for spatially distributed detectors, which determines the sky area of the most probable localization of the source. The time of the signal registration is measured with a high accuracy; however, the localization area may be very large, tens to hundreds of square degrees (see Table 1). GW170817 [16] has a localization region of ~30 square degrees, and there were reported ~190 galaxies in the volume limited by the sky area and distance estimates [17]. The kilonova AT2017gfo was discovered independently by 6 survey projects and was observed during several dozens of days in wide energy range from X-rays to radio [18]. The co-authors of the paper were used the mosaic method to search for optical counterpart, observed of kilonova and proposed the model of prompt emission of GW170817/GRB 170817A [19].

In this paper, we discuss the problem of the search of a new transient optical source in large areas provided by detections of gravitational wave sources. We describe two basic methods of the search: mosaic observations of localization area and pre-determined goals observations, i.e. search for transients in galaxies inside the detection volume. We also provide several examples of such semi-manual searches using available ground-based optical telescopes performed during the LIGO/Virgo observational run O2. Multi-messenger Astronomy is becoming a commonplace [20].

Table 1. Selected source parameters of the eleven confident GW detections [21]

Event	Type [a]	d_L/Mpc[b]	$\Delta\Omega$=deg^2[c]
GW150914	BBH	430 (+150/-170)	180
GW151012	BBH	1060 (+540/-480)	1555
GW151226	BBH	440 (+180/-190)	1033
GW170104	BBH	960 (+430/-410)	924
GW170608	BBH	320 (+120/-110)	396
GW170729	BBH	2750 (+1350/-1320)	1033
GW170809	BBH	990 (+320/-380)	340
GW170814	BBH	580 (+160/-210)	87
GW170817	BNS	40 (+10/-10)	16
GW170818	BBH	1020 (+430/-360)	39
GW170823	BBH	1850 (+840/-840)	1651

[a] BBH – binary black holes. BNS – binary neutron stars.
[b] Luminosity distance.
[c] Error box of sky localization.

2 The Optical Transient Search Procedure

After receiving the alert signal from LIGO/Virgo, our observations are carried out on ground-based optical telescopes to search for counterpart.

One can observe the whole range of localization with wide-field telescopes. This observation tactic is suitable if the localization area is not very large (up to about one hundred square degrees), or it is possible to observe on a large number of telescopes.

Since we know not only the localization region in the celestial sphere of the gravitational-wave event, but also the distance to the source, we can only observe galaxies from the localization region that are located at a given distance. For this purpose, there is a value-added full-sky catalogue of galaxies, named as Galaxy List for the Advanced Detector Era, or GLADE [22]. GLADE was constructed by cross-matching and combining data from five separate (but not independent) astronomical catalogues: GWGC, 2MPZ, 2MASS XSC, HyperLEDA, and SDSS-DR12Q. But GLADE is complete up only to d_L=37(+3/-4) Mpc in terms of the cumulative B-band luminosity of galaxies within luminosity distance d_L, and contains all of the brightest galaxies giving half of the total B-band luminosity up to d_L=91 Mpc. While the distance to the registered source can be several thousand Mpc (see Table 1).

But whatever method we use, we need to find a transient on the obtained optical images.

We use the method of comparison with all-*sky catalogs* using the generated catalog of sources selected from the image. A block diagram of the method is presented in Fig. 2.

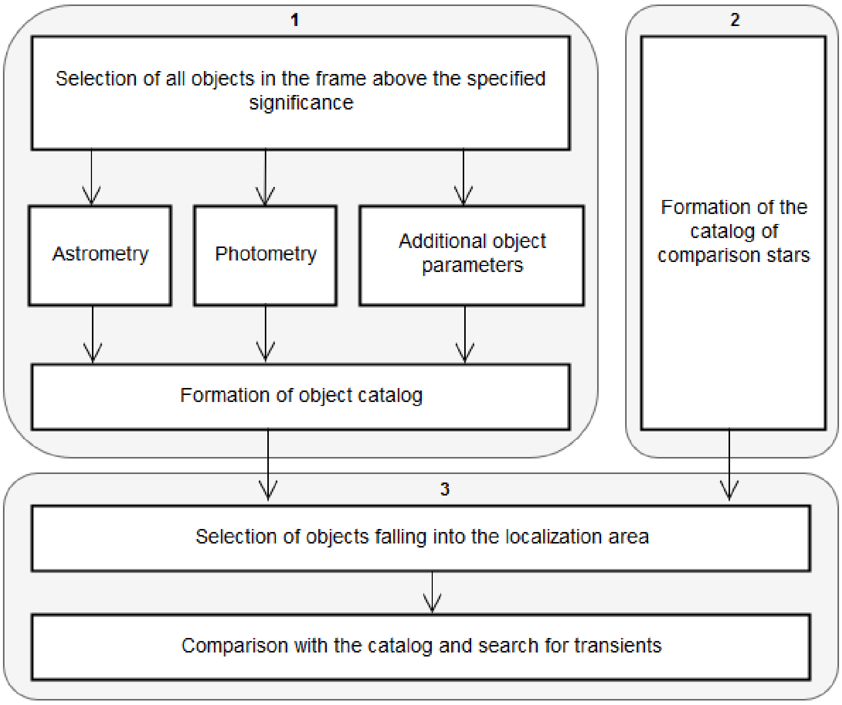

Fig. 1. A block diagram of the match algorithm

Block 1 – detection, measure and classification of sources from astronomical images, the formation of an object catalog. In this case, we used SExtractor – software for source extraction [23]. Comparison of object catalogs is best done using equatorial coordinates of objects; first of all, astrometry is necessary (for example, using Apex [24] or other software). To avoid incorrect comparison, it is useful to reject objects at the border of a frame that do not fully fit into the frame (either at a distance of < 4 FWHM from the border or to use the value of the SExtractor flags).

Block 2 – formation of the catalog of the comparison stars. For comparison of objects it is better to use photometric catalogs (e.g. SDSS, Pan-STARRS, APASS, 2MASS, it depends on the filter of the original image, the image upper limit and the region of the celestial sphere).

Block 3 – search for transient sources.Comparison of objects is performed simultaneously by equatorial coordinates and magnitude within the measurement error.

3 Results Obtained for our Procedures of Search and Identification

Our collaboration is based at the Space Research Institute and provided follow-up gravitational wave observations in the optical range during Second Observing Run of LIGO/Virgo.

The optical data were obtained by IKI GRB Follow-up Network which is collaborating with Crimean Astrophysical Observatory (CrAO), Sayan Solar Observatory (Mondy), Tian Shan Astrophysical Observatory (TShAO), Abastumani Astrophysical Observatory (AbAO), Special Astrophysical Observatory (SAO), ISON-Khureltogoot, Koshka observatory of INASAN and Byurakan Astrophysical Observatory (BAO).

3.1 LIGO/Virgo G299232: Compact Binary Coalescence Candidate

GW170825 G299232is a low-significance compact binary coalescence candidate identified from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) at 2017-08-25 13:13:31 UTC. If the candidate is astrophysical in origin, it appears consistent with the merger of a black hole and a neutron star [25]. Subsequently, the event was not confirmed.

Localization generated by the BAYESTAR pipeline [26] including information from H1, L1, and V1 is presented in Fig. 1. The 90% credible region spans about 2040 deg^2. The a posteriori luminosity distance estimate is 339 +/-110 Mpc [25].

The IceCube Neutrino Observatory (a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica) searched IceCube online track-like neutrino candidates (GFU) detected in a [-500,500] second interval about the LIGO/Virgo trigger G299232 [27]. Comparison of the candidate source directions of 7 temporally-coincident neutrinos to the BAYESTAR skymap is presented in Fig. 2.

One of the neutrino candidate (marked as X1) was within the LIGO/Virgo localization area and detected 233.82 seconds before LIGO/Virgo trigger G299232.X1 sky location is R.A.=28.2, Dec.=44.8 with 3.8 degrees uncertainty of direction reconstruction [28].

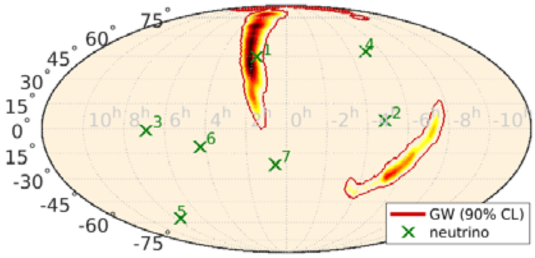

Fig. 2. The localization with distance information generated by the BAYESTAR pipeline [26] including information from H1, L1, and V1.X1 - X7 are neutrino candidates (GFU) detected in a [–500,500] second interval about the LIGO-Virgo trigger G299232

We observed the field of LIGO/Virgo trigger G299232 [25] and error circle of IceCube candidate X1 [27, 28] with wide field of view VT-78a telescope of ISON-Khureltogoot observatory. We obtained several unfiltered images with the two time series starting on 2017-08-25 (UT) 15:24:13 and 16:32:52 (time since LVC trigger are 0.11289 and 0.16054 days), each centered to the position of localization reported in [27] and [28], respectively. Total coverage of the error region of IceCube candidate X1 [28] is 85.7 %. The map of the coverage can be found in Fig. 3.

Using the algorithm described in Chapter 3 we have distinguished 94.7 thousand objects from the images (field of view is 7 x 7 degrees). After comparing these 94.7 thousand objects with the USNO-B.1 catalog we have 834 candidates left, of which 818 are processing artifacts. Finally, we found one cataloged asteroid (895) Helio and 24 objects, the magnitude of which was brighter than R2 of USNO-B1.0, but weaker than R1 (see Table 1). There is no presented R-magnitude for the object 1352-0033439 in USNO-B1.0 catalog, but magnitudes B1=18.27, B2=15.32 and I=13.87 for the object 1352-0033439 are presented in catalog and correspond to our photometric magnitude (column name is “Mag SExtractor” in Table 2).

We found no significant variability of the sources between the two epochs. We found no significant brighter sources, which could be galaxies, than their R-magnitudes presented in the USNO-B.1 catalog. Upper limit on the stellar magnitude of possible optical candidate is 19.2.

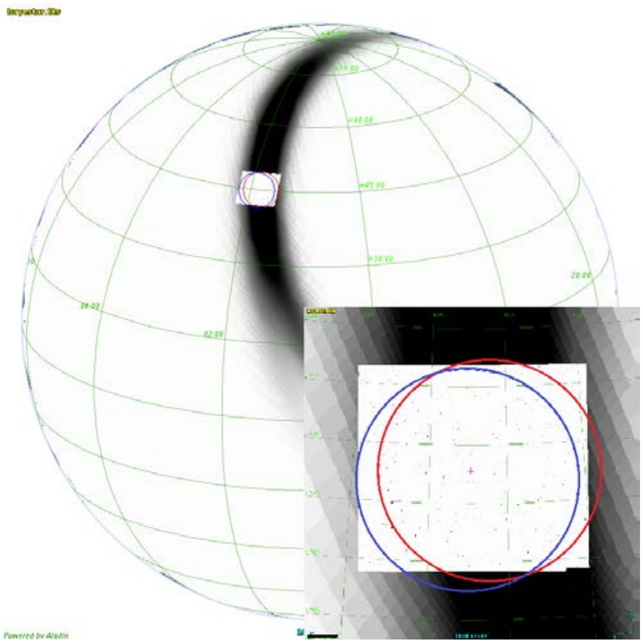

Fig. 3. The map of the coverage IceCube candidate X1 localization by VT-78a telescope of Khureltogoot observatory. Red circle is preliminary IceCube X1 error box [27], blue circle is final error box [28]

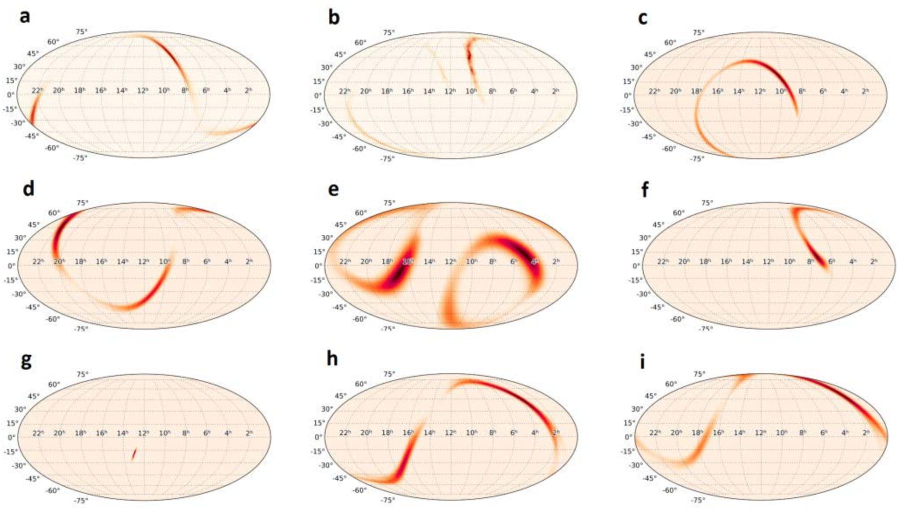

Fig. 4. Sky localization of LIGO/Virgo events. a – GW170104_G268556, b – GW170120_G270580, c – GW170217_G274296, d – GW170227_G275697, e – GW170313_G277583, f – GW170608_G288732, g – GW170817_G298048, h – GW170823_G298936, i – GW170825_G299232

Table 2. List of object which magnitudes are brighter than R2 of USNO-B1.0

USNO-B1.0 id	R1	R2	Mag SExtractor
1377-0046508	13.51	16.26	14.22
1377-0046571	15.49	18.48	16.41
1377-0046983	14.23	20.16	14.80
1378-0048129	11.44	14.42	12.40
1378-0048633	15.51	18.38	16.20
1378-0048730	13.89	16.87	14.49
1377-0048562	15.79	19.76	16.48
1377-0048684	13.69	16.37	14.34
1376-0047873	14.53	18.27	15.06
1372-0048226	15.56	19.83	16.30
1355-0039997	14.13	17.78	14.92
1352-0033439	-	-	16.46
1327-0048518	13.94	18.19	14.11
1328-0048333	14.47	17.22	14.87
1327-0048405	15.19	20.70	15.79
1328-0048274	13.14	15.59	13.31
1324-0046318	19.27	-	15.76
1327-0038107	12.93	19.03	13.68
1327-0038122	15.42	20.47	16.24
1328-0038377	11.94	15.03	12.66
1328-0038222	12.87	18.22	13.66
1328-0038148	12.68	19.20	13.61
1328-0038142	14.50	20.47	15.29
1328-0038084	14.11	18.98	14.92

3.2 Observations of LIGO/Virgo Optical Candidates

In addition to searching the object in the localization area, we also observed objects in the localization area of GW events that were found by other research groups.

The objects that we have observed are listed in the Table 3, the areas of localization of each gravitational-wave event can be seen in the Fig. 4. Some gravitational-wave events, the areas of which we observed, later were not officially confirmed and continue remained candidates.

Table 3. Observations of optical candidates of LIGO/Virgo events

Event	Type [a]	Optical candidates	Type[b]
GW170104_G268556	CBC (+) [29]	PS17fn	n/c
		PS17fl	n/c
		PS17dp	n/c
		PS17gl	n/c
GW170120_G270580	n/c (-) [30]	PS17yt	SN Ia
		MASTER OT J090737.22+611200.5	n/c
		PS17lk	n/c
		PS17nv	n/c
		PS17pv	n/c
		PS17qk	n/c
		PS17rc	n/c
GW170217_G274296	n/c (-) [31]	PS17bek	SLSN
GW170227_G275697	CBC (-) [32]	iPTF17bue	SN Ia
		XRT23	n/c
GW170313_G277583	n/c (-) [33]	ATLAS17cgg	SN IIn
GW170608_G288732	BBH (+) [21]	GW170608X2	n/c
GW170817_G298048	BNS (+) [21]	GW 170817	GRB, KN
GW170823_G298936	BBH (+)[21]	GWFUNC-17ure	SN Ia
GW170825_G299232	NS+BH (-) [34]	SwiftJ014008.5+343403.6	n/c
		MASTER OT	SN IIb

[a] BBH – binary black holes merging, BNS – binary neutron stars merging, NS+BH – neutron star and black hole merging, CBC – compact binary coalescence, n/c – this event candidate does *not* have a chirp signature, and thus does not suggest a compact binary merger or the morphology of the event candidate is unclear. (+) – event, (-) – candidate.
[b] SN – supernova, KN – kilonova, SLSN – super-luminous supernova, GRB – gamma-ray burst, n/c – non classified.

GW170120_G270580. The Pan-STARRS covered northern area of the GW170120_G270580 localization and detected 124 transients including rapidly rising transient – PS17yt (R.A. 10:03:57.96 Dec. +49:02:28.3) [35,36]. Our collaboration observed PS17yt source in BVR filters and a light curve of PS17yt were constructed (see Fig. 5a). It was subsequently shown that PS17yt is Ia type supernova at a redshift z ~ 0.026 [37].

Furthermore, we observed orphan sources PS17lk (R.A. 09:29:58.27 Dec. +15:11:58.5), PS17nv (R.A. 09:57:41.01 Dec. +17:49:33.4), PS17qk (R.A. 09:29:12.15 Dec. +25:49:06.4), PS17pv (R.A. 09:25:07.35 Dec. +50:12:28.9), PS17rc (R.A. 09:32:19.16 Dec. +47:03:38.3) and MASTER J090737.22+611200.5 (R.A. 09:07:37.22 Dec. +61:12:00.5) in the field of the LIGO G270580 localizations. Results of observations see in Table 4.

GW170217_G274296. Pan-STARRS covered 501 square degrees on the first night following the release of the G274296 alert. They have located and vetted 10 transients with host spectroscopic redshifts and 60 unknown transients with no host spectroscopic redshifts. [38] We observed one of the transients with no host spectroscopic redshifts (PS17bek) and the light curves in BR-filters are presented in Fig. 5b.

Afterwards a good correlation betweenPS17bek spectrum and the spectra of superluminous supernovae (SLSNe type I) was found. In particular, a good match with the spectra of SN 2010gx at -5 days before peak if PS17bek is at a redshift of z~0.31 was found. The weak emission line at 6559.4 is consistent with [O III] 5007 at z=0.31, and we also detect [O III] 4959 at a consistent redshift but lower significance [39].

GW170825_G299232. Global MASTER robotic net discovered optical transient source – MASTER OT J033744.97+723159.0(R.A. 03:37:44.97 Dec. +72:31:59.0). [40]. Analysis of the MASTER spectrum suggests that it is a supernova Type IIb [41] MASTER OT observation with the RoboPolpolarimeter shown that the R-band fractional polarization of the source is 1.8+/–0.47% [42].

Our observations of the MASTER OT are shown in the Fig. 5c.

4 Summary

In 2017, coordinated hardworking of thousands of astronomers and other scientists around the world allowed to find and successfully observe the electromagnetic counterpart of the gravitational wave event GW170817 of binary neutron star merging. The associated GRB 170817A and kilonova AT2017gfo were observed by hundreds of space and ground-based experiments in all ranges of electromagnetic spectrum. The unprecedented collaboration allowed to obtain detailed properties of kilonova and to verify existing physical models of this phenomenon, which is not fully studied yet. At the same time, there was no any reliable EM counterpart candidate detected for 10 binary black holes coalescences discovered during O1/O2 scientific runs of LIGO and Virgo detectors. However, a huge amount of observational data, which covered vast localization area of the events, led to the discovery of many other new transient sources unrelated to the GW. The problem of search of a new optical transient with specific properties in large localization areas arose here with the great actuality.

Table 4. The photometric observation results of orphan sources

Orphan	Date	Filter	MJD	Magnitude
PS17lk	2017-01-25	R	57778.72969	20.92 +/– 0.16
	2017-01-29	R	57782.74483	> 22.5
	2017-01-30	R	57783.70939	21.10 +/– 0.11
	2017-01-31	R	57784.69874	21.22 +/– 0.12
	2017-02-07	R	57791.93095	21.60 +/– 0.40
	2017-02-18	R	57802.73167	21.89 +/– 0.24
PS17pv	2017-01-25	R	57778.82847	>20.5
	2017-01-28	R	57781.86958	>22.4
	2017-01-30	R	57783.80134	20.74 +/- 0.11
PS17nv	2017-01-25	R	57778.74557	>22.2
	2017-01-27	R	57780.82339	>22.2
	2017-01-31	R	57784.03700	>23.4
PS17qk	2017-01-25	R	57778.77275	21.01 +/– 0.12
	2017-01-29	R	57782.78859	20.61 +/– 0.11
	2017-01-30	R	57783.74301	20.46 +/– 0.06
	2017-01-31	R	57784.73083	20.36 +/– 0.05
	2017-01-31	R	57784.84479	20.50 +/– 0.03
	2017-01-31	B	57784.85668	20.87 +/– 0.04
	2017-02-01	R	57785.77138	20.17 +/– 0.05
	2017-02-18	R	57802.75716	20.55 +/– 0.07
	2017-03-06	CR	57818.86623	20.53 +/– 0.09
PS17rc	2017-01-25	R	57778.81470	20.96 +/– 0.15
	2017-01-30	R	57783.77229	21.04 +/– 0.10
	2017-01-31	R	57784.76358	21.13 +/– 0.11
	2017-01-31	R	57784.88885	21.28 +/– 0.05
	2017-01-31	R	57784.87345	23.57 +/– 0.24
	2017-02-01	R	57785.80742	21.28 +/– 0.09
MASTER OT	2017-01-21	R	57774.62327	19.07 +/– 0.01
J090737.22+611200.5	2017-01-22	R	57775.64491	19.10 +/– 0.02
	2017-01-23	R	57776.63227	19.18 +/– 0.03

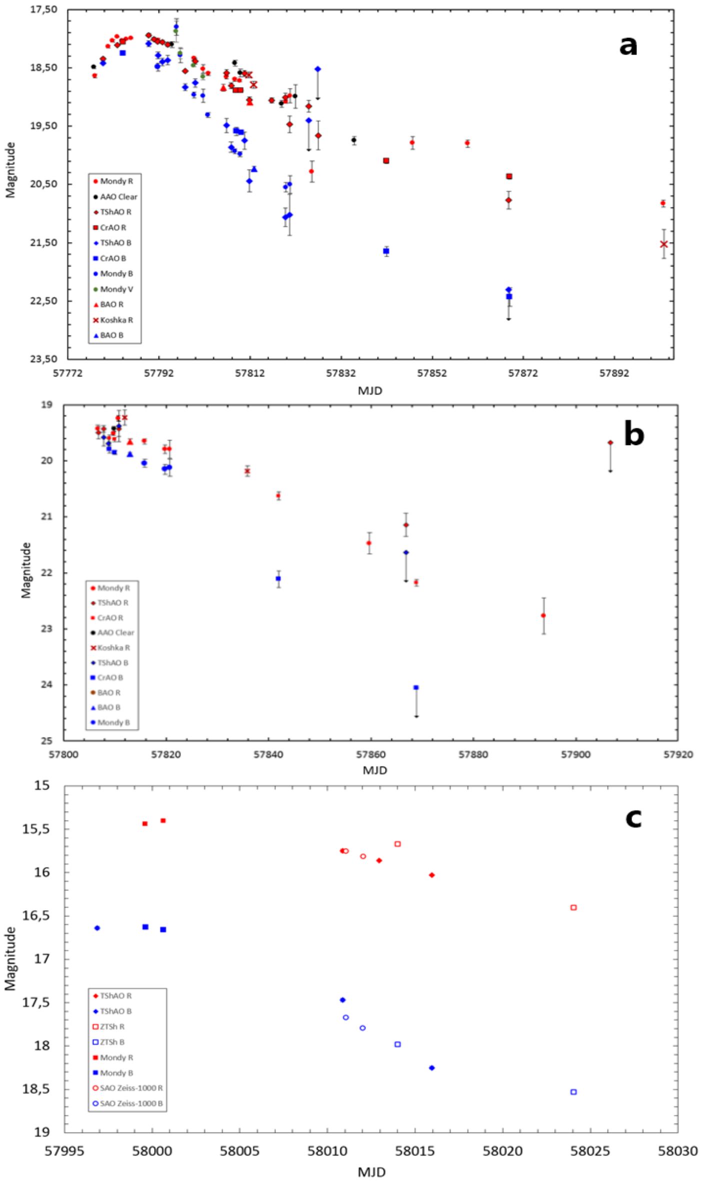

Fig. 5. a – light curves of PS17yt (GW170120_G270580 optical candidate), b – light curves of PS17bek (GW170217_G274296 optical candidate), c – light curves of MASTER-OT (GW170825_G299232 optical candidate). Red points are R-band, blue points are B-band and green points are V-band. Observations were obtained by TShAO (Zeiss-1000), CrAO (ZTSh – 2.6m), Mondy (AZT-33IK), AAO (AS-32), BAO (ZTA 2.6-m), Simeiz/Koshka (Zeiss-1000). Host galaxy is not subtracted

We discussed the two main methods of the search for optical transients in the areas of tens and hundreds of square degrees: mosaic surveys and observations of pre-defined targets (potential host galaxies). The case of mosaic surveys is suitable for small-aperture telescopes with wide fields of view, with rather low optical upper limit, though. The search of the transient inside pre-defined target galaxies requires deeper limits and thus require observations with large-aperture telescopes with >1 meter diameter. The second case involves compiled catalogues of galaxies with known distance like Galaxy List for the Advanced Detector Era (GLADE) [22]. This fact increases the actuality of deep surveys of galaxies with measured distances. These methods are suitable not only for the search of the EM counterpart of gravitational waves events detected by LIGO/Virgo, but also for the search of optical counterparts of ordinary GRBs with large localization region (e.g., from GBM/Fermi experiment).

We also provided results of the observations of localization regions of candidates for real GW events detected with LIGO/Virgo during their second scientific run O2. We did not find any optical transients with our facilities; however, we conducted a follow-up of transients discovered by other teams worldwide. This valuable experience is now being adapted for the third scientific run O3 of LIGO/Virgo, which started on April 1, 2019 and would continue for 1 year. Nevertheless, the problem of automatization of the data processing algorithms remains unsolved for all cases and requires the development of new conceptual approach, and generalized pipelines for data reduction are required.

Almost all space and ground-based astronomical facilities are now involved in the follow-up of GW events. This makes multi-messenger astronomy a commonplace nowadays. Quick availability of new obtained data and vast collaboration of observatories and observers may guarantee further success.

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