Multi-messenger astronomy: the alert observations of gamma-ray bursts afterglows, supernovae and search for optical counterparts to neutrino events and gravitational waves

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Abstract On the strategy for the all SAO telescopes for the study and monitoring of afterglows of cosmic gamma-ray bursts (GRBs), optical identification of sources of gravitational waves and neutrino signals from supernovae, fast radio bursts (FRB). We plan to carry out (to continue) follow-up observations of localization areas (identification) of newly-discovered gamma-ray bursts, neutrino and gravitational signals, and supernovae (in the mode of Target of Opportunity Observation). The telescopes: BTA, Zeiss-2000 (TB INASAN), Zeiss-100 (SAO RAS) in the modes of photometry, spectroscopy, fast photometry and polarimetry. Alerts from missions Swift, Fermi, INTEGRAL, Lomonosov and others. The aim of the search for optical/electromagnetic components with SCORPIO and MANIA at BTA is the sources (related to GRBs) of neutrino and gravitational waves (GW events) detected by LIGO (Laser Interferometer Gravitational-wave Observatory) and Virgo.

Keywords: Gamma-Ray Bursts Afterglow, Neutrino Signals, Gravitational Signals

1. Introduction

In the early 21st century there appeared new challenges for the ground-based astronomy. These include:

- gamma-ray bursts observed in 1978-1997;
- gravitational wave signals. The signal GW150914 was detected on September, 14, 2015, by two detectors LIGO in Hanford and Livingston with 7 msec separation. But the error box is too large – about 1000 sq.deg, so, there was no identification yet. The event GW170104 has similar values. Last events were modeled by coupling of NS;
- neutrino events: SN1987A is the only reliable event so far, but the international projects ICECUBE, ANTARES , etc. are going on;
- FRB – Fast Radio Bursts discovered in 2007, with the 64-m Parks 13-beam radio telescope [3]. There was the first identification with a radio galaxy at z=0.5).

See Proceedings of the International Workshop “Quark Phase Transition in Compact Objects and Multimessenger Astronomy: Neutrino Signals, Supernovae and Gamma-Ray Bursts” held by SAO RAS and BNO INR RAS in 2015 [1] (https://www.sao.ru/hq/grb/conf_2015/proceedings.html) and Proceedings of the International Conference “SN 1987A, Quark Phase Transition in Compact Objects and Multimessenger Astronomy” held by BNO INR RAS and SAO RAS in 2017 [2] (https://www.sao.ru/hq/grb/conf_2017/proceedings.html).

2. Observations in SAO RAS

Reliable identification demands optical identification.
The rates of expected events are as follows:

1. Gamma-Ray Bursts – 2-3 per week
2. Gravitational events (3 or 4 during the recent 1.5 years)
3. Neutrino events (several ones per year)
4. Fast Radio Bursts – less than 10 so far.

Observations are possible only in the ToO (Target of Opportunity) mode.
How can Special Astrophysical Observatory of RAS meet the challenge today?
We have a rather wide range of available ground-based facilities:

- BTA + complexes of spectroscopy, photometry, and fast photopolarimetry (Figs.1,2,3,4);
- Zeiss-1000 + a CCD photometer (the field of 7′) and the low-resolution spectrograph (Figs.5, 6).
- MiniMegaTORTORA – a multi-channel wide-angle complex of subsecond temporal resolution (the FOV about of 900 sq.deg.)
- Zeiss-2000 of Terskol Branch of INASAN + a CCD photometer (FOV - 11′) + a moderate-resolution spectrograph
- ShMT+ CCD photometers (the FOV of 9′ and 20′)

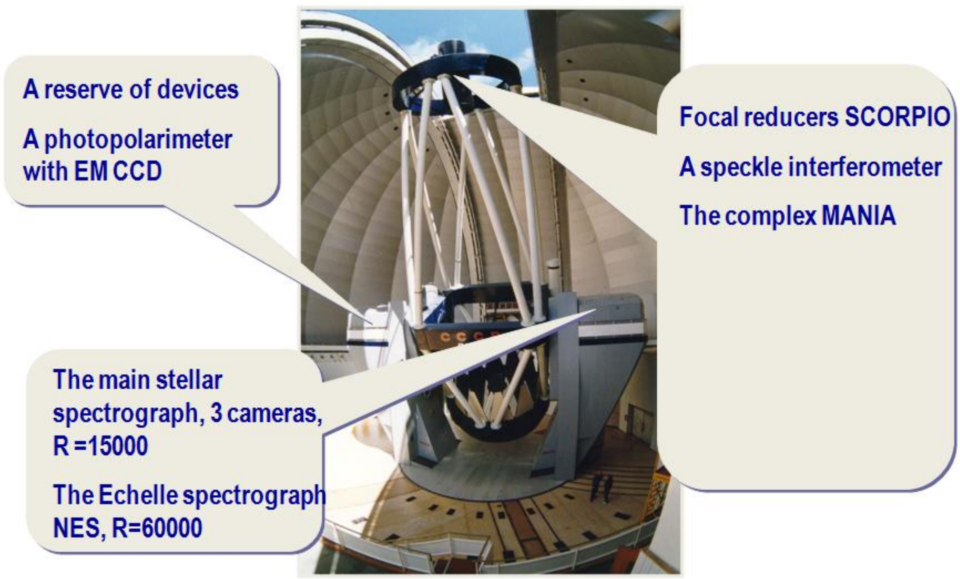

Fig1. *The 6-meter telescope and its main devices.*

Fig2. *Layout of the Spectral Camera with Optical Reducer for Photometrical and Interferometrical Observations (SCORPIO).*

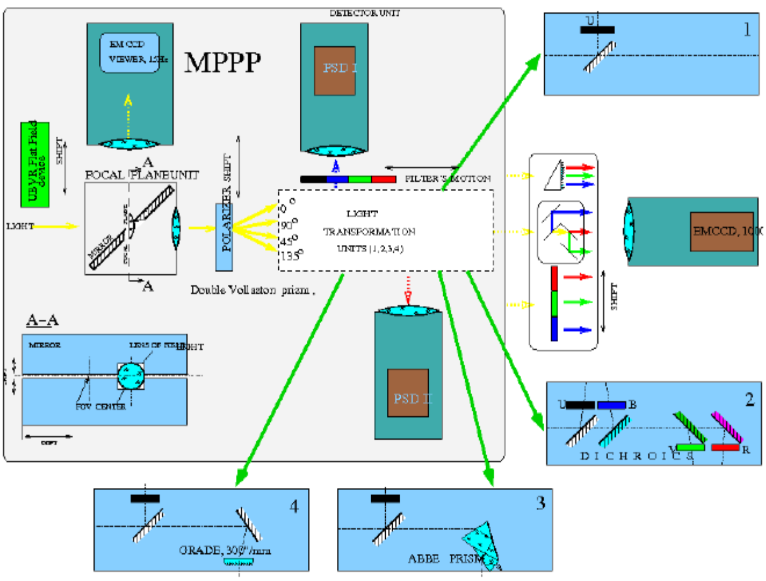

Fig3. *The complexe for studying fast variability in the BTA Primary Focus (PF). MANIA for studying microsecond variations. Scheduled in the BTA about 10-15 nights per year. Performance capabilities: wide-band photometry (up 1 microsec) and polarimetry, low-resolution spectroscopy.*

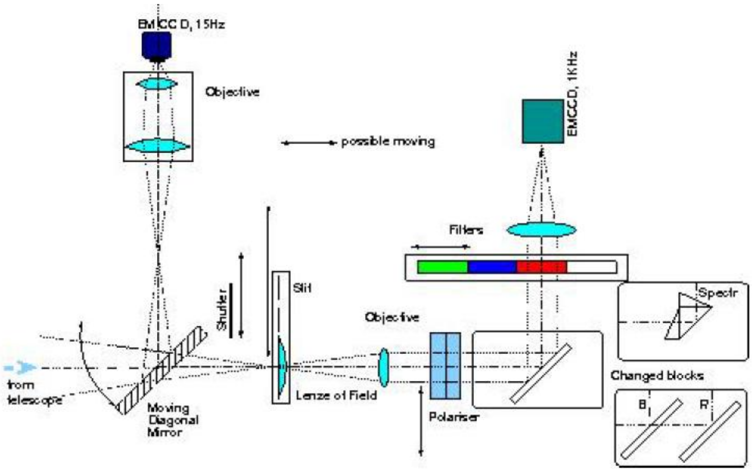

***Fig4**. The complex for studying fast variability in the BTA Nasmith-1 (N-1) focus. N-1: a complex in "hot standby": it will operate in the second half of 2018. Can be started up during several minutes. It includes the EM CCD with the temporal resolution till 1 msec. Performance capabilities: wide-band photometry and polarimetry.*

***Fig5.** Small SAO's telescopes. Top left: general view of the domes. Right: the 1-meter telescope Zeiss-1000. Bottom left: the 60-cm telescope.*

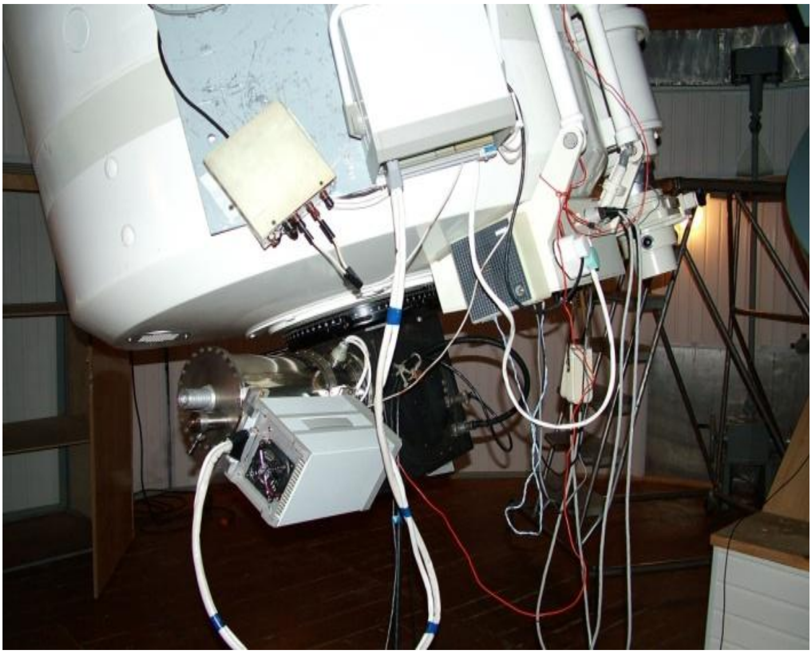

Fig6. *Equipment of the 1m telescope: a CCD photometer with 2048x2048px by 13.5 microns. The field of view is 7'. The limit stellar magnitude is 23.5 mag. The medium-band photometry in UBVRI filters + narrow-band filters.*

SAO also uses the multi-channel wide-angle telescope of high temporal resolution Mini-MegaTORTORA since 2014. Performance capabilities are as follows: 9 channels with the field of view of 100 sq.deg., the threshold of magnitude – about 11.5 st.magn. during 0.1s or 15 st.magn. during 60s. There is a project of extending the system. See also Fig. 1 in the paper "Search and study of optical transients with Mini-MegaTORTORA" by N.V. Orekhova et al. in these Proceedings.

Also some equipment is planned for the nearest future:

- a photopolarimeter in Nasmith-1 ("hot standby"),
- a fast photopolarimeter of the 1m telescope,
- a complex of small telescopes with the fields of 1°.

But we need large-aperture telescopes with large fields and gigapixel CCD detectors.

3. The study of Gamma-Ray Bursts (GRB) in SAO RAS

Gamma-ray bursts are the brightest transient sources. The multiband observations of GRBs (after 1997) confirm that a considerable part of so called "long" GRBs is related with collapse of short-lived massive stars.

Fig.7 shows the MMT study of the gamma-ray burst GRB160625B.

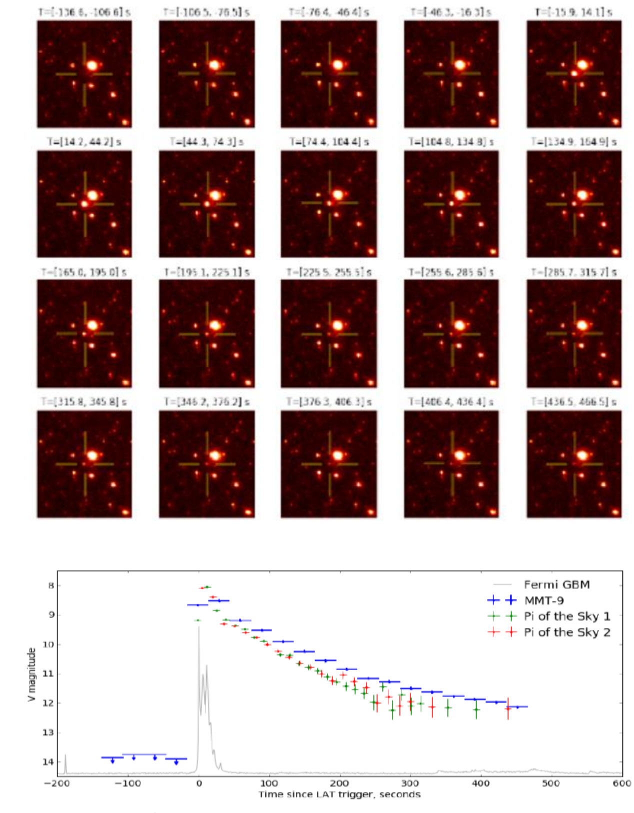

Fig7*. The MMT study of GRB160625B. Operation by a precursor at -180 sec. The study in the field of 30x30°. Texp=30sec. The lag of optics in comparison with gamma-rays is about 3 sec. Top: optical images. Bottom: time diagram.*

4. Some results of our team

4.1. The study of the GRB 021004 field

The results of the field galaxies clustering in GRB lines of sight based on the BTA observations and with other instruments are presented in the paper “The field galaxies clustering in GRB lines of sight based on observations with BTA and other telescopes” by I.V. Sokolov, A.J. Castro-Tirado, I.A. Solovyev, O.V. Verkhodanov, O.P. Zhelenkova, and V.V. Sokolov in these Proceedings.

The characteristic signs of the clustering of field galaxies were detected in the direction to the gamma-ray burst GRB 021004.

All accessible signs of such clustering in the line of sights and near the location of GRB021004 were tested.

The data from observations with BTA/SCORPIO, HST/ACS, VLT/UVES and from the cluster catalog SDSS-III were used.

On the excess density of field galaxies near z ~ 0.56 around the GRB 021004 position

We test for reliability any signatures of field galaxies clustering in the GRB 021004 line of sight.

The first signature is the GRB 021004 field photometric redshifts distribution based on the BTA observations with a peak near z ~ 0.56 estimated from multicolor photometry in the GRB direction.

The second signature is the Mg II 2796/2803Å absorption doublet at z ≈ 0.56 in VLT/UVES spectra obtained for the GRB 021004 afterglow.

The third signature is the galaxy clustering in a larger (~ 3×3 degrees) area around GRB 021004 with an effective peak near z ~ 0.56 for both the spectral and photometric redshift distributions obtained from the Baryon Oscillation Spectroscopic Survey (BOSS), which is a part of the Sloan Digital Sky Survey III (SDSS-III).

A possibility of inhomogeneity (a galaxy clustering) near the GRB 021004 direction can be also confirmed by an ***inhomogeneity*** in cosmic microwave background related with the Sunyaev-Zeldovich effect.

From catalogs data, ***the size*** of the whole inhomogeneity in distribution of the galaxy cluster with the peak near z ≈ 0.56 was also estimated as ~6-8 degrees

It is also well proven that long-duration GRBs are associated with the core collapse of very massive stars.

Similarly to core collapse SNe, the collapse of massive stellar iron cores results in the formation of a compact object (collapsar), accompanied by the high-velocity ejection of a large fraction of a progenitor star mass at relativistic speed producing a series of internal shocks giving rise to the GRB itself.

Namely, the determination of distance to SNe and GRBs resulting from collapse of compact objects of stellar mass becomes the main observational task in determining a basic parameter: **the total energy release related to such events**.

The collapse of the massive stellar cores maybe connected with the quark phase transition in the compact objects, which leads to neutrino, gravitational and photon signals from the core collapse SNe (like SN1987A) and GRBs.

It is also obvious that for low and intermediate redshifts, the sky distribution of electromagnetic and neutrino signals associated with the core-collapses can be nonisotropic, **showing the clustering of galaxies** in which the formation of compact objects occurs due to evolution of massive stars.

5. Prospects

TASK:

THE STUDY AND MONITORING of sources of cosmic gamma-ray bursts, *identification* of sources of gravitational waves and neutrino signals from supernovae, fast radio bursts.

We plan to carry out (to continue) follow-up observations of localization areas ***(identification)*** of newly-discovered gamma-ray bursts, neutrino and gravitational signals, and supernovae (in the mode of "Target of opportunity Observations" (ToO)).

The telescopes: BTA, Zeiss-2000 (TB INASAN), Zeiss-1000 (SAO RAS) in the modes of photometry, spectroscopy, fast photometry and polarimetry.

Alerts : from missions*Swift, Fermi, INTEGRAL, Lomonosov and others.*

The alerts from the MiniMegaTORTORA system (SAO RAS) are possible.

In addition, we aim at the search for optical/electromagnetic components (related to GRBs) sources of neutrino and gravitational waves (GW events) detected by LIGO (Laser

Interferometer Gravitational-wave Observatory) and Virgo.

6. International cooperation

The works as a part of program in an international observational collaboration:

1. In optical:

with teams from the German-Spanish Observatory Calar Alto (Spain, 2.2 and 3.5 m for imaging and spectroscopy),

observatory La Palma (Spain, the telescopes of 1-2m for photometry, 4.2m and 10.4m GTC for photometry and spectroscopy),

the Observatory Nainital (the 1.0m telescope, the 1.3m telescope Devasthal for imaging),

In near IR range the telescope AZT-24 (MAO RAS, Campe-Imperatore, Italy).

2. Radio observations will be fulfilled with the 30-meter radio telescope IRAM (Spain), the 32-meter telescopes of IAA RAS and with the telescope GMRT (India).

It is proposed to combine the observations with the robotic telescopes of the MASTER-II network of the MASTER Net (Moscow, Kislovodsk, Amur, Urals, Spain, Argentina, South Africa).

7. The strategy of study.

Alert signals from space gamma-raymissions, neutrino observatories (we are interested in ICECUBE and KAMIOKANDE), LIGO&VIRGO.

Fast radio bursts – for the time being the search is made with the Parks 64m telescope (the Southern sky).

It is planned to start searching for FRBs with RATAN-600.

It is possible to use the data from MiniMegaTORTORA.

Stage 1: IDENTIFICATION (the specification of coordinates with the 1m and 2m telescopes in the photometry mode, for very large error boxes – the identification with MiniMegaTORTORA) and prompt transfer of coordinates to BTA and other telescopes.

Stage 2: STUDY (photometry in BVRcIc bands with 1-2m telescopes up to R~22, with BTA – spectroscopy of objects brighter than R~22 in the range 350-950 nm for determining z of the source and obtaining absorptions on the line of sight, resolution (depending on the source brightness), fast photometry and polarimetry with the complex of fast variability in the first minutes and hours after the burst, then – photometry with the deep limit up to R~25).

CRITICAL – photopolarimetry for determination of the collapse geometry, the expected polarization is of order of 10%.

Stage 3: BTA low-resolution PHOTOMETRY and SPECTROSCOPY of different phases of the source evolution – the appearance of the second peak in luminosity, spectral features of supernovae.

In conclusion we would like also to emphasize here that since GRBs are detected at more and more distant cosmological distances with redshifts more than 9.2, this poses additional new questions which are of outmost importance for observational cosmology.

What are the redshifts at which the sky distribution of GRBs becomes homogeneous?

And what are the redshifts where such bursts (which are related now with collapse of compact objects of stellar mass) are unobservable already?

THE PROBLEM

This strategy does well for identification of sources with good error boxes. Here our advantage is the fast reaction and geographic location.

In case of neutrino and gravitational signals, data of fast radio bursts, the coordinate precision is not sufficient yet; the telescopes with large fields and good limits are necessary.

In the West: the operating PAN-STARRS and SkyMapper, DEC, etc.

Coming soon: the 8.4-m Large Synoptic Survey Telescope (LSST).

8. Our plans for the future

1. The project off a new large-aperture telescope with large field (this is not decided yet).
2. New equipment for BTA: a spectrophotometer of the IR range (is being made)
3. Manufacturing of a series of effective moderate-resolution spectrographs for telescopes of the 2m class (a prototype is being used with AZT33IK of ISTP RAS).
4. Creation of a photometer-polarimeter for the 1m telescope (is planned for 2017-2018)
5. Creation of a network of small telescopes (up to 6 items with D=0.5-0.6m and the field of view about 1 sq.deg.) equipped with CCD photometers with large cameras (up to 4Kx4K elements).

Tasks: the monitoring in fields about 1 degree, photometry of bright sources.

The project starts in Summer 2017, observations – in 2018.

8.1. A telescope of new Russian technology (TNRT)

The prototype – the 4.1m telescope VISTA ESO

The main tasks: the study of transient sources: GRB, SN, neutron events, deep surveys in wide fields, etc.

The project status: preliminary, under discussion.

Time of creation: 2018-2023.

The TNRT design is shown in Fig.8. Some TNRT equipment is presented in Figs. 9, 10.

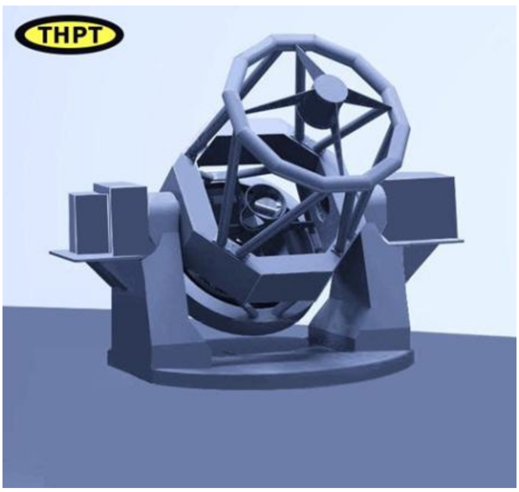

Fig8. *TNRT design*

The main characteristics of the telescope

- Alt-azimuthal mounting
- Optical layout – quasi Ritchey-Chretién
- Diameter of the main mirror – about 3.5(4) m
- MM material – sitall CO-115M (Zerodur)
- Focuses: Cassegrain, 2 (4) Nasmith
- Spectral range: 0.35 – 1.7 (2.5) microns
- Angular resolution (optical) - not worse than 0.”5
- The operational field - 2° (3 °)
- It is expected that there will be systems of active optics of MM, a system of wave front adaptation in a small field.
- Implementation of the technology of spraying high-effective reflecting coatings with R up to 97% in a wide range.
- Equipment: Cassegrain for photometry in wide fields: mosaics up to 20kx20k px (optics) and 8K×8K (IR), Nasmiths – for integral field spectrograph and scanning Faby-Perot interferometer, multi-object spectrograph for 300-500 objects.

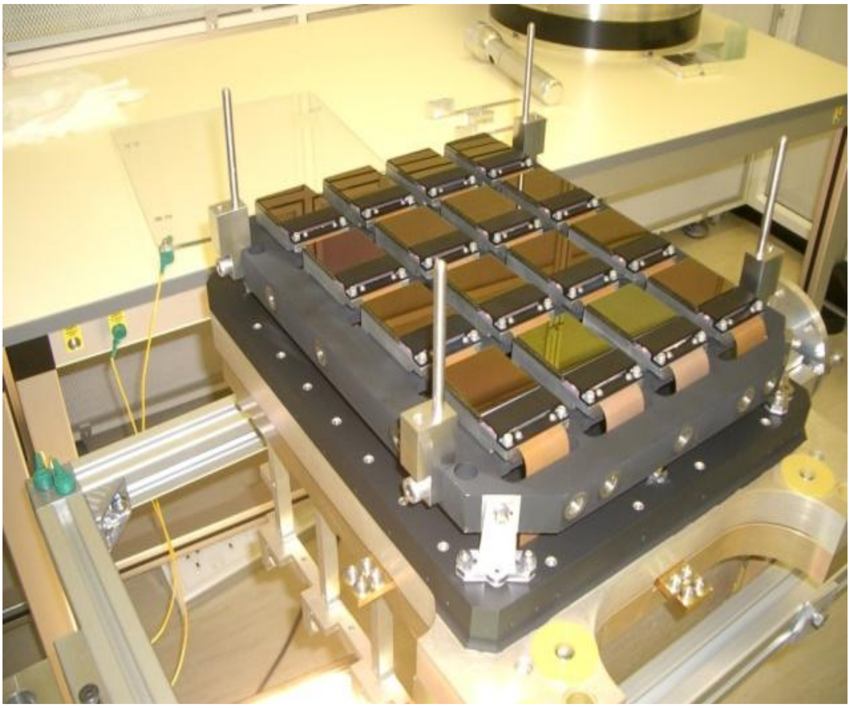

Fig9. *TNRT: a view of the large-field IR camera. Size of the field of view: up to 1° × 1°. Scale: 0.3 – 0.5 arcsec/px. The set of filters: Wideband J, H, K; medium-band (FWHM ~200-300 A). Detector: mosaic HAWAII-2 Location : the Nasmith focus*

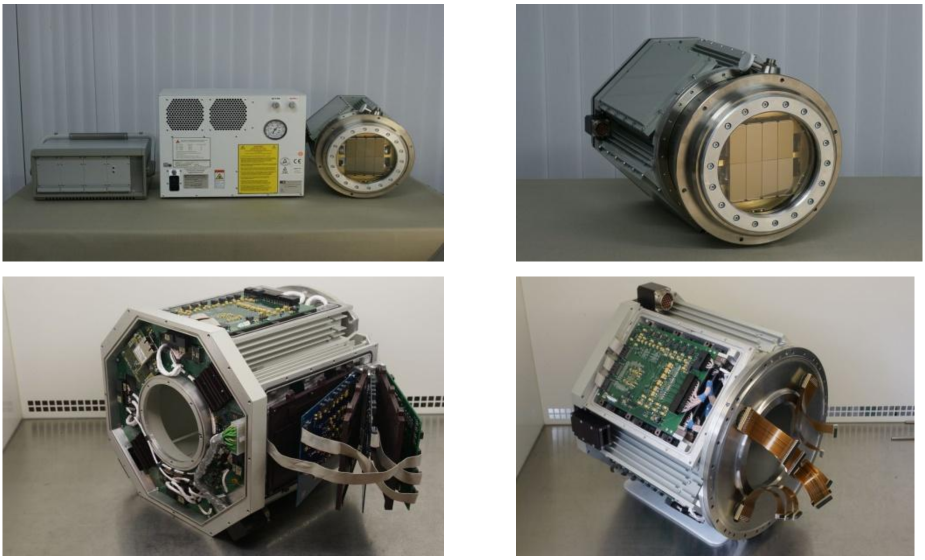

Fig10. *Technical groundwork for TNRT: photodetector with a mosaic sensor*

8.2. Complex of the 0.5-m robotic telescopes at SAO RAS

A complex of 0.5-meter robotic telescopes is being in constructed in SAO RAS. Some views of the process are presented in Figs. 11,12.

Fig11. *Construction of the complex. Left: September 2017. Right: December 2017.*

Fig12. *One robotic telescope.*

The main scientific goals are as follows:

- GRB: small robotic telescopes detect optical signal, measure it's parameters and within few seconds pass data to 6-m for detailed studies.
- FRB: synchronous observations with RATAN-600 (expecting rate – 8 ev per year).
- Photometrical studies of exoplanets and magnetic stars.
- Alert observations of SNs, Novae, CV, QSO, NEO etc
- Observational programs: students, teachers etc

Conclusion.

- For reliable identification of transients (from gamma-ray, radio, neutrino and gravitational) it is necessary to carry out optical observations
- Equipment of SAO and other telescopes in whole is ready for observations of transient sources of a new class.
- Successful implementation of the projects demands a wide international cooperation and implementation of plans of development of instrument base.

References

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[9] Thornton et al, 2013, Nature