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Slewing mirror telescope of the UFFO-pathfinder: first report on performance in space

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Abstract: To observe the early optical emissions from gamma ray bursts (GRBs), we built the Slew Mirror Telescope. It utilizes a 150 mm motorized mirror to redirect incoming photons from astrophysical objects within seconds and to track them as compensating satellite movements. The SMT is a major component of the UFFO-pathfinder payload, which was launched on April 28, 2016, onboard the *Lomonosov* satellite. For the first time, the slewing mirror system has been proven for the precision tracking of astrophysical objects during space operation. We confirmed that the SMT has 1.4 seconds of response time to the X-gamma-ray trigger, and is able to compensate for satellite drift and to track astrophysical objects with magnitudes from 7 to 18.

OCIS codes: (350.6090) Space optics; (110.0110) Imaging systems; (350.1260) Astronomical optics.

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1. Introduction

One of most important astrophysical objects for emerging multi-messenger astronomy are Gamma-Ray Bursts (GRBs) [1]. Observation of GRBs [2–7] accompanied with gravitational waves [8] are among the chief interests in space science and shed light on the brightest events in universe, including merging neutron stars [9–13]. NASA's *Swift* [7] space observatory was the first mission to provide GRB data across a range of optical / UV bands. One limitation of the *Swift* instrument is that its observations require the reorientation of the entire spacecraft towards GRB destination, which takes ∼ 100 seconds [14].

The UFFO-pathfinder [15, 16] is a pilot project, that was launched in April 2016 onboard the *Lomonosov* [17] satellite. Its key instrument, named the Slewing Mirror Telescope (SMT) [18, 19], employs a rapidly moving motorized mirror (see Fig. 1), that redirects the optical path of telescope towards GRB in order to obviate the necessity of reorienting the entire spacecraft. As consequence, UFFO-pathfinder has a reaction time on the order of a single second and is able to study a much earlier time domain of GRB emission.

For the detection and localization of GRB events at X-ray wavelengths, the UFFO Burst Alert and Trigger Telescope (UBAT) is used [20, 21]. The UBAT is a coded mask camera with $70° \times 70°$ half coded FoV, able to localize bright GRBs within a 1 second integration time. The UBAT employs 48×48 YSO scintillator crystal array connected to photomultipliers, with 191 cm^2 of total detection area and a 5 ∼ 150 KeV sensitivity range. Both the UBAT and the SMT are controlled by the UFFO-pathfinder Data Acquisition system (UDAQ) [22].

Since its launch, we have demonstrated the validity of slewing mirror telescope technology, the key concept of UFFO-pathfinder instrument. We conducted a series of *in situ* performance tests of the SMT. The present study focuses on the results of these experiments and is organized as follows. Section 2 provides an overview of the SMT hardware, describes the SMT data acquisition

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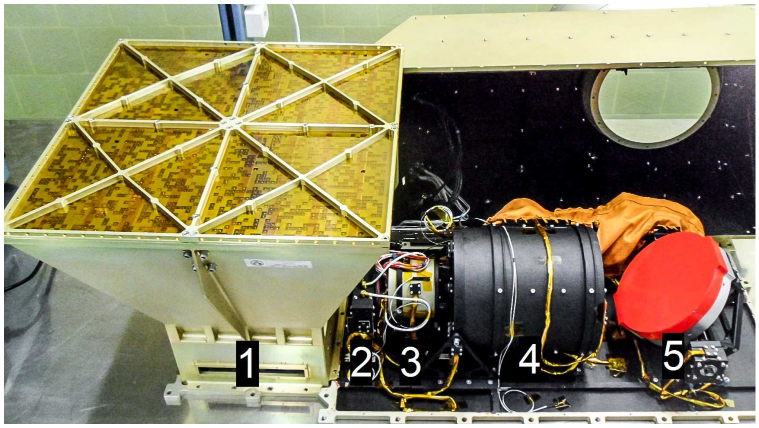

Fig. 1. Ultra-Fast Flash Observatory pathfinder. (1) - UFFO-pathfinder Burst Alert and Trigger Telescope (UBAT) - X-ray coded mask camera, used for triggering and localization of GRBs; Slewing Mirror Telescope: (2) - Readout electronics; (3) - Intensified charge-coupled device detector (ICCD); (4) - 10 cm RC Telescope; (5) - Slewing mirror system (the mirror is under a red protection cover prior to launch).

strategy and presents the expected performance of the SMT in terms of sensitivity to signal (GRB) and background (diffused photon flux on the SMT and the number of stars inside SMTs FoV). Section 3 reports the results of SMT performance tests in space, and discussions of the findings follows in Section 4. Finally, we provide a summary in Section 5.

2. Instrument overview

2.1. Slewing mirror telescope

The SMT consists of 100 mm Ritchey-Chrétien telescope detailed in [18]; slewing mirror system and readout electronics [23]. The instrument has a $17' \times 17'$ FoV and a resolution of $4.2''$ over 256×256 pixels. The SMT is built to cover the half-coded FoV of UBAT [20], i.e. $\pm 35°$ through the utilization of its slewing mirror. The SMT is capable of observing GRBs in single-photon mode with an intensified charge-coupled device (ICCD) consisting of two layered multi-channel plate (MCP) situated on the focal plane (the same method is employed by the UVOT [14]). Two gimbal motors drive the slewing mirror with sub-arcsec positioning, demonstrating a one second response time across the entire FoV. Commercial rotary encoders and the stepping motors with sealed bearing systems provide a sufficiently rapid response to meet the UFFO-pathfinder scientific requirements. They are simple, robust and mostly space qualified.

The readout electronics collect the ICCD data, communicate with the UDAQ, control the mirror position, and monitor the housekeeping sensors. The SMT employs Field-Programmable Gate Array (FPGA) as its main processing component, and thus is able to achieve faster response times for incoming triggers while simultaneously running many additional processes (data taking and sending, mirror moving, housekeeping monitoring and so on). The FPGA controls all clock signals, motor power, ICCD high voltage and ICCD gain. Readout electronics are proved to be reliable in extreme environments and meet all requirements for operating in space.

The SMT is designed to observe the unexplored early time domain of the GRB optical light curve that typically persists from first second up to several tens of seconds. The default total observation time in SMT is 80 seconds. The first 880 frames have 20 ms exposures, and last 820 frames have 40 ms exposure times. There is also 20 ms blind time between frames. Single event size is limited to 113,520 Kbits, as shown in Table 1, due to bandwidth restrictions for data transmission to Earth.

Table 1. SMT data size

Frame size		Event data size	Daily data
ICCD data	Housekeeping		
256×256 bit	512 byte	1700 Frames	4 Events
8.5 KB		14.45 MB	57.8 MB

Despite the fact that the SMT is capable of a 10-bit color depth, we selected 1-bit uncompressed images. The expected photon flux inside the SMT FoV from background and signal was small enough for 1-bit color, however, yet not so large as to call for data compression. Section 2.2 opens the subject to a more detailed discussion.

2.2. Expected source rates and backgrounds

Considering the main SMT parameters, the expected values were given for SMT sensitivity at specified source magnitudes. Values of the diffuse background as well as the randomly varying star count, which will appear in the SMT's FoV, were calculated before flight as well.

The single frame exposure time for the SMT is 18.6 ($\approx$ 20) ms; input telescope diameter is 10 cm; and the input quartz window efficiency and total optics is efficiency are 0.95 and 0.56, respectively. Assuming a total photon flux from a Vega-type zero magnitude star to be 10^6 photons/second/cm^2, and the ICCD S20 photocathode efficiency $Q_e(\lambda)$ as given in [23], we determined the limit for single frame sensitivity of the SMT as a function of incoming signal magnitude to be $\sim$ 1 photon per frame at magnitude 11. Zero point of the SMT is 15 magnitude.

Only a few sources contribute in diffuse backgrounds for telescope a operating above the atmosphere [24]. Most significant of them is *zodiacal light* (ZDL) - scattered sunlight reflected by interplanetary dust particles in the solar system. Other background sources, such as *extragalactic background light* and *diffuse galactic light*, are $\backsim 10^2$ times less intense. We adapted [25] reference of diffuse night sky brightness for estimation of ZDL spectrum and flux, and a detailed map of ZDL intensity in terms of photons/frame for the SMT is provided on Fig. 2. Depending on the solar ecliptic coordinates, the amount of background ZDL photons registered in single ICCD frame will vary between 20 to 100, with an average value of 50. For estimation of stellar density, we used the USNO-B [26] all-sky star catalog, which has been assembled from various sky surveys taken over the last 50 years, and is presented in B and R filters. The B2 filter was chosen because of its proximity to our sensitivity range. The number of stars in the SMT FoV averaged over galactic longitude as a function of galactic latitude is given in the Fig. 3. The number of stars (mag $\leq$ 11) within the SMT FoV is expected to be not exceeding 2 for the majority of possible FoV coordinates. This value is one order smaller than the expected number of photons from zodiacal light, and may be omitted from assessments of background values. Nevertheless, such stars remain important as additional coordinate references when interpreting SMT data: 5-7 stars in the SMT FoV make possible the utilization of astrometry.

3. Performance in space

The UFFO-pathfinder was launched on 28 April 2016 and first turned on in June 2016. After that, a series of tests was performed. In this section, we discuss the STM's space performance and provide proof of concept for the use of slewing mirror systems above the atmosphere.

3.1. Observed issues

The first several tests provided no data from the UFFO-pathfinder despite the fact that triggers had been produced by the UBAT. At the default setting, data is not taken unless the mirror reaches

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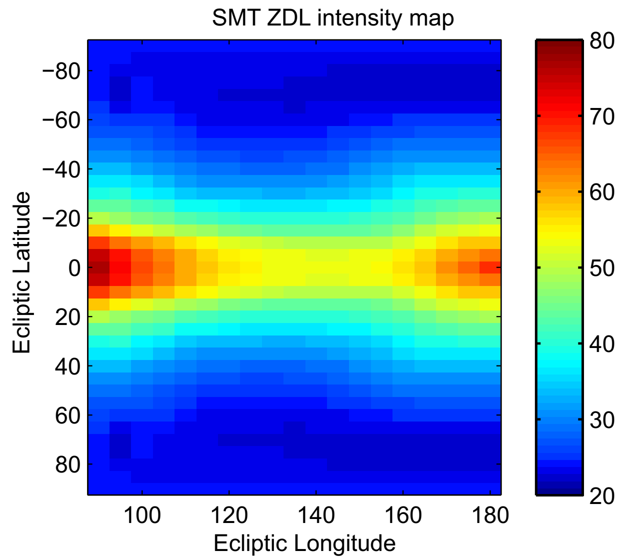

Fig. 2. Map of expected zodiacal light [24] photon flux for the SMT in solar ecliptic (Sun oriented) coordinates. At least 20 photons from zodiacal light are expected per 20 ms frame, with the count sometimes exceeding 60 photons.

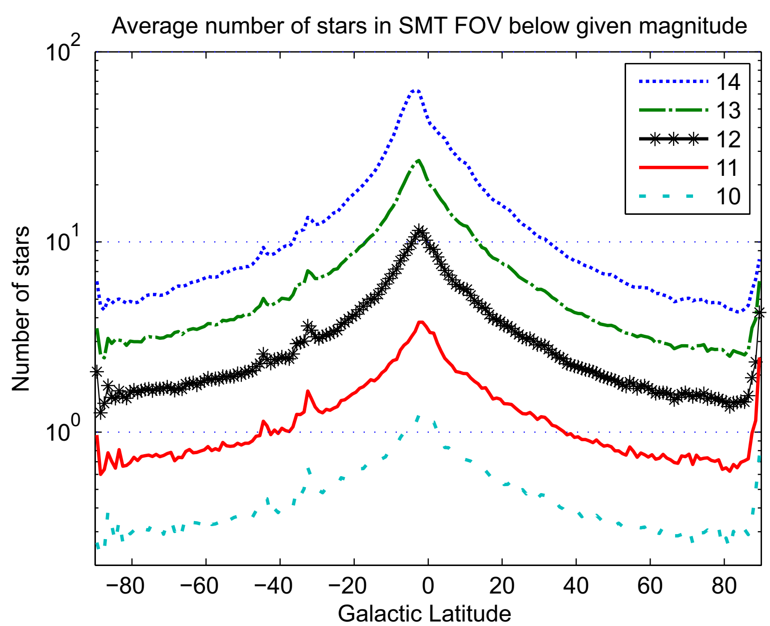

Fig. 3. The average number of stars in the SMT FoV depending on Galactic Latitude, for B magnitudes not exceeding given values. The count for magnitude 11 is on average 1 photon per 20 ms exposure, and will be seen on 62% of frames (due to Poisson distribution). Stars with greater magnitudes will be observed for longer exposures.

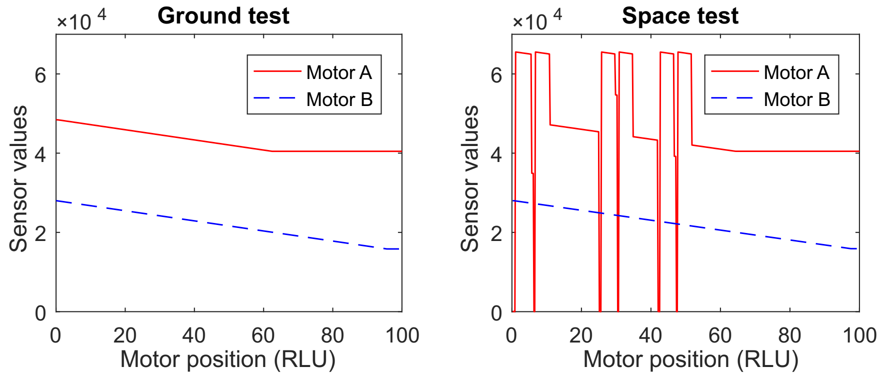

Fig. 4. Results of mirror position reading system tests on the ground and in space. The right plot demonstrates breakdown of the motor A position reading system following launch: for some positions of motor A, the feedback system provides incorrect angle values.

correct trigger position, for which reason the motor system was suspected as a possible cause of the failure.

Detailed analysis indicated a problem in the mirror position reading system: the commercial decoder board (VK10S08B0AN, Gurley Precision Instrument) was working incorrectly. The decoder board utilizes two sensors to read the position values for motors A and B, writes each motor position as a 16-bit value and transports them to the main SMT's FPGA. The decoder board began sending incorrect position values (see Fig. 4) for most of the possible motor A positions. Two separate plots show the results of the mirror position reading system tests on the ground and in space; the horizontal axis corresponds to the real motors positions and the vertical axis corresponds to the 16-bit values sent by the decoder board to the main SMT's FPGA. In normal operation, this dependence must be linear, as in the case for the ground data. However, motor A showed a completely different pattern after launch. We suspect cosmic radiation environment damage to the decoder FPGA logic as a possible explanation for this hardware failure.

As a consequence, the main SMT board could not receive correct data regarding current mirror positions, even though the motors were working properly.

Possible problems with mirror position reading system were foreseen before the flight, and some precautions were taken. We implemented several programming options, to allow the motor to rotate "blind", or without feedback. Accuracy for this mode is of a $2'$ order, which is lower it would be with feedback. A further disadvantage is that without a position reading system we cannot certain that the slewing mirror is properly oriented. In this case, astrometry remains the only way to check the coordinates of the SMT FoV.

3.2. Rapid slewing capability after trigger

The main purpose of the UFFO-pathfinder is to study the first seconds of GRB prompt optical and UV emissions. Therefore, the response times of the SMT following a UBAT trigger is among the most important UFFO-pathfinder parameters. Table 2 provides the results of five SMT response time measurement tests for given triggering by the UBAT. In general, response time is smaller, when the target position is close to the initial mirror position, as in case for the November 10, 2016 data.

Despite the mirror position reading system problems just described, a 1.4 ± 0.3 second response time is still possible, and thus the SMT remains fully compliant with the scientific goal of the UFFO-pathfinder mission.

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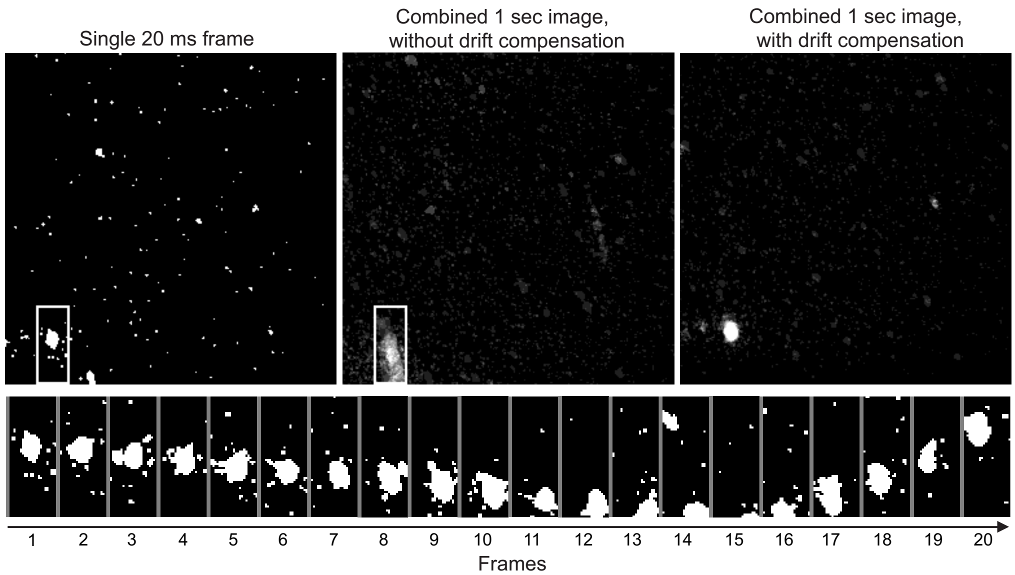

Fig. 5. **Left**: single 1-bit 20 ms exposure frame. Bright star (Tycho-2 1206-461-1) is selected to illustrate the FoV drift. **Central**: 20 frames are combined without drift compensation - image blurred, track of bright star may be observed. **Right**: same frames combined with full drift compensation - the resolution became better - beside a bright star, two dim stars become observable. Bottom: movement of the bright star on over 20 frames. **Bottom**: frames 1-15: star is drifting downward due to satellite rotation. Frames 16-20: with telescope FoV correction by the slewing mirror, the star's position within frame returns to the proximity of its initial exposure position. Frame 20: The mirror drift compensation finish; star is returned to its original position with $\sim 1'$ mistake.

3.3. Tracking performance toward astrophysical object

The SMT is the first space telescope to utilize a slewing mirror system for tracking astrophysical objects. Its FoV is $17'$, and the FoV drift speed is $4'$/second (this is speed of orbital movement of *Lomonosov*): thus, without drift correction, the FoV will change completely after 4 seconds. However, the SMT slews its mirror in response to the *Lomonosov* rotation, and the FoV remains static.

Correction of the FoV is performed once per second. Figure 5 (bottom) shows the drift of the FoV over a one second interval (frames 1-15) and its compensation by the mirror system (frames 16-20). Each succeeding 1-bit frame is shifted from the previous. At frame 20, the image of the bright star returns nearly to the same position within the frame that was observed for the first frame exposure. The FoV correction error is around $1'$ (with a mirror position reading system it could be more precise - see Section 3.1). As can be seen in the top center panel of Fig. 5, combining the frames without software drift compensation leads to a blurred final image. This imperfection in the operation of the motor system is overcome on the ground, utilizing data combination software to determine the 2D cross correlation function between images with slightly different FoVs. The result of both mirror drift correction and ground software frame combination for that 20 frames is shown on the top right panel of Fig. 5.

Despite small errors in the mirror drift correction, the SMT can track astrophysical objects for 150 seconds - see Table 2. Thus, the slewing mirror system fully meets its scientific goal - the SMT is able to observe the first 100 seconds of GRB activity.

Table 2. Slewing mirror performance: response time to the trigger and tracking time - time for a stable FoV (maximal time for which a target could be observed by the telescope). Target position is given in the UFFO-pathfinder's system of coordinates, with mirror initial position in the center.

Date	Target position		Response	Tracking
(in 2016)	X, degree	Y, degree	time, sec	time, sec[b]
Sep 26	8.58	−25.67	1.36	148
Sep 29	13.67	−19.67	1.72	88
Oct 4	13.75	−19.18	1.08	40
Oct 20	10.45	1.28	1.47	170
Nov 10	−4.55	5.92	1.04	191

3.4. Sensitivity & angular resolution

We present part of our data in Fig. 6. This image was taken over a 40 seconds exposure on September 26, 2016 during a telescope sensitivity test. The scale represents the often-used count rate of photons per 1000 seconds, and the different exposure times as well as ICCD efficiencies of the individual pixels are taken into account. The telescope captured enough photons to observe stars with B magnitudes of up to 16, and white magnitudes of up to 15. The star IDs are taken from the Tycho-2 catalog. As a magnitude check, USNO-B1.0 catalog B2 magnitudes are given (in blue), and GSC 1.2 catalog magnitudes (in white). The white spots around the periphery of the image are background fluctuations; the real exposures at that areas were small, and as a consequence relative fluctuations are very high. The image size is larger than $17' \times 17'$=256×256 pixels due to the slewing mirror operation. Each 256×256 1-bit frame was taken from a slightly different FoV; and when they are summed up with shift, the final image size increases. In total, the slewing mirror system performed 74 drift corrections over the course of the entire Fig. 6 exposure.

As was determined prior to launch and reported in [18], the point spread function of the SMT has a $4.2''\sigma$. To prove that the SMT was not damaged during launch and its sensitivity and resolution did not change, we conducted several on-orbit tests of the instrument.

The measured background is shown in Fig. 7. For measurement of background, we took only the areas where no stars were found with B2 mag. >21.5 from the USNO-B1.0 catalog. The Poisson fit value of 5.365 hits per CCD pixel per 40 seconds was used for the calculation of signal to noise ratio (SNR) and the estimation of sensitivity described in Section 4.

The details of the angular resolution are given in Fig. 8. The data was taken on July 25, 2016 with the exposure of 2 seconds. The mirror drift correction was turned off to check the angular resolution which turned out to be $4''$ (sigma of the Gaussian fit) for faint stars. For brighter stars, the value is larger. Note that the vertical axis of Fig. 8 is SNR in logarithmic scale for different star magnitudes, where a central pixel in the image of 12.6 B magnitude star reaches an 18σ confidence level for an exposure time of 2 seconds.

3.5. Measured photon flux in the SMT FoV

The measured photon flux and the number of stars in our FoV for SMT observations are shown in Table 3. The SMT detects on average 60 photons for 20 ms frame. The result reflects not only zodiacal light but all sources. Those values in the table are in accordance with expected calculations for zodiacal light (25-100 photons as shown in Section 2.2) and expected average number of stars in the SMT FoV - see Fig. 3.

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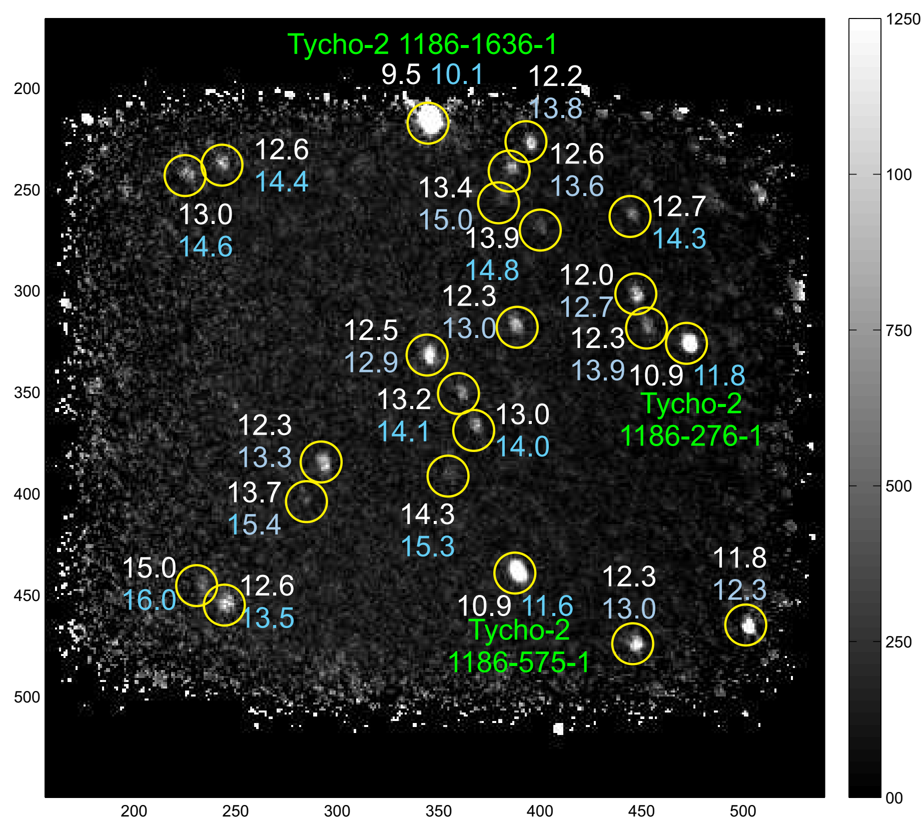

Fig. 6. Results of SMT sensitivity in space for a 40 seconds exposure. The telescope captured enough photons to observe stars with B magnitudes of up to 15; white magnitudes up to 14. Counts are given for a 1000 seconds estimation. For each pixel, individual exposure times and ICCD efficiencies are considered. We performed magnitude checks against the USNO-B1.0 catalog B2 magnitudes (in blue), and GSC 1.2 catalog magnitudes (in white). Data is taken from September 26, 2016 during a UFFO-pathfinder test.

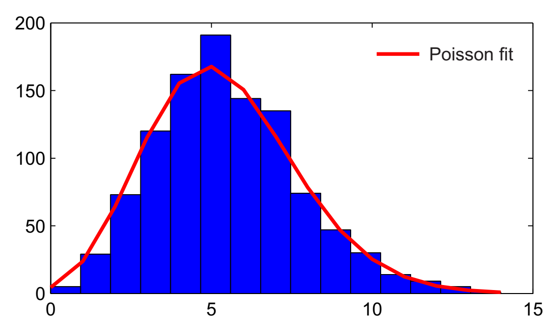

Fig. 7. Histogram of number of hits over single CCD pixel from September 26, 2016 data. Exposure is 40 seconds, and 1039 pixels were taken into the plot. Red line - Poisson distribution fit.

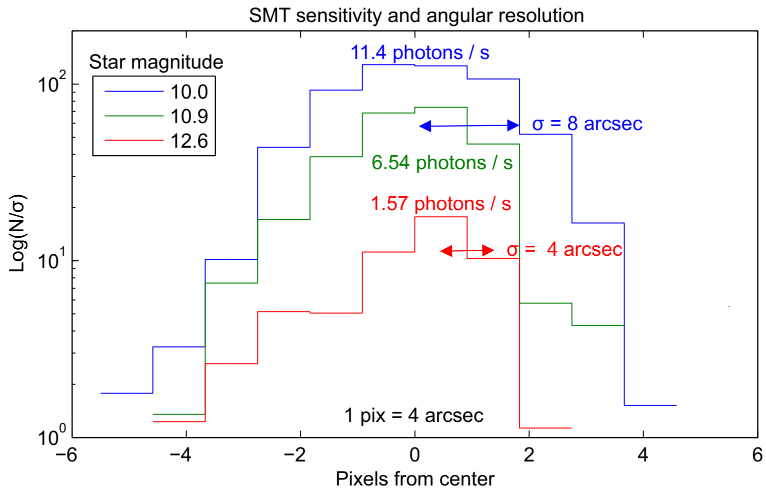

Fig. 8. Results of SMT angular resolution in space. Background σ = 0.089. For point source, angular resolution is around 4′′. For bright stars it may rise to 8′′. Signal is normalized to 1 second observation time. Magnitude B2 from USNOB1.0 catalog. Star IDs are 2090-949-1, 2091-1264-1 and 2091-1235-1 Tycho-2 catalog. Data is taken from July 25, 2016 UFFO-pathfinder test.

Table 3. Diffuse background and number of stars in the SMT data

Date	Galactic coordinates		Photon	Number of stars with B magnitude	
(in 2016)	Longitude	Latitude	flux	≤ 12	≤ 15
Jul 5	40.95	37.83	24 ± 11	4	12
Sep 8	58.89	−55.28	64 ± 14	2	11
Sep 26	115.99	−40.85	61 ± 8	3	21
Sep 29	121.26	−48.98	72 ± 10	5	15
Oct 4	119.02	−47.63	73 ± 9	4	9
Oct 20	144.50	−45.23	88 ± 10	5	11

4. Discussion

The concept of a slewing mirror telescope has been proven in space. The SMT has a rapid response time - down to 1 second, and can maintain a given FoV for more than 150 seconds despite the problem that emerged within mirror position reading system after launch.

Regarding sensitivity, we observed that the SMT has a 1 photon per frame count rate for stars with a B magnitude of 11 (or a white magnitude 10). During the 50 seconds of default exposure time, the SMT acquired enough data to detect stars of B magnitude 16. Considering that SNR$\sim \sqrt{time}$, the SMT is able to see 18 mag on the 1000 seconds scale. This result was obtained from raw data without any software improvement such as centeroiding done by *Swift*, so we expect to detect much dimmer stars with the technique like centeroiding

Our measurement result is in good agreement with the prediction for the diffuse background and star density within the SMT FoV.

Our space tests showed that the SMT has a response time of less than 1.7 second and can track astrophysical objects with magnitudes of up to 16 for more than 150 seconds. GRB apparent magnitude distribution has a maximum at 19.5 magnitude for 1000 sec exposure [27]. Observations of GRB optical and UV afterglow by the UVOT [14] have a typical brightness

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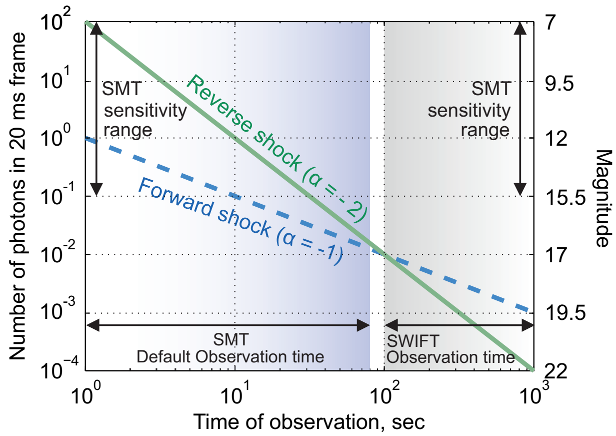

Fig. 9. Expected GRB brightness and number of photons for 20 ms SMT frames SMT proven sensitivity range is wide enough for expected brightness of GRB prompt optical emission.

decline of between $t^{-1.1}$ and $t^{-2.1}$ - Fig. 9. With its hundredfold faster response time, the SMT is allowed 5-10 magnitudes less sensitivity, than the UVOT. During its first second of observation time, the SMT is able to detect 12 magnitude of GRB brightness; thus, the SMT is proven to be sensitive enough to observe the rising light curves of GRBs.

5. Conclusions

The Slewing Mirror Telescope is the first telescope to utilize a motorized mirror to change the optical beam path. The feasibility of this concept is now proven by the successful performance of the SMT in space. From now on, the slewing mirror approach may be used for other space missions. As with the *Lomonosov*, this design will be especially useful on spacecrafts with multiple payloads, like *Lomonosov*, where the rotation of the entire satellite is not allowed because it would change the field of view of other payloads. Typical examples are interplanetary missions - they always have many payloads, and must keep orientation, with antenna looking towards Earth.

After launch, the SMT encountered a problem with one of its mirror position sensors. This problem was overcome by a special software option, which enables mirror movement to occur without feedback. Following the resolution of this problem, the SMT has been calibrated by the an *in-situ* method. Currently, the UFFO-pathfinder is operating in orbit and the SMT is ready to observe much earlier phases of GRB optical and UV emission. The SMT will provide much insight into prompt emission at time regimes never systematically studied by other observatories. The results of GRB detection by the SMT will be reported in our following papers.

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