Status report of the UFFO-pathfinder

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Abstract: Gamma-Ray Bursts (GRBs) are the most energetic explosions in the universe, their optical photon flux rise very quickly, typically within one minute, then fall off gradually. Hundreds of GRBs optical light curves have been measured since the first discovery of GRB in 1967. However, only a handful of measurements have been made within a minute after the gamma ray signal. Because of this drawback, the short-hard type GRBs and rapid-rising GRBs, which may account for 30% of all GRBs, remain practically unexplored. To reach sub-minute timescales, the Ultra-Fast Flash Observatory (UFFO) uses a rapidly moving mirror to redirect the optical beam instead of slewing the entire spacecraft. The first realization of this concept is UFFO-pathfinder, which is equipped with fast-response Slewing Mirror Telescope (SMT) and a UFFO Burst Alert and Trigger Telescope (UBAT). SMT has a slewing mirror to redirect optical photons into a telescope and then record them by an intensified CCD. UBAT uses coded mask to provide X-ray trigger from a GRB and provides the GRB location for SMT. UFFOs sub-minute measurements of the optical emission of dozens of GRBs each year will result in a more rigorous test of current internal shock models, probe the extremes of bulk Lorentz factors, provide the first early and detailed measurements of fast-rise GRB optical light curves, and help verify the prospect of GRB as a new standard candle. The UFFO-pathfinder is fully integrated with the Lomonosov satellite and is scheduled to be launched in late 2013 or early 2014. We will present the latest progress in this conference.

Keywords: Gamma Ray Burst, Satellite Instruments, Coded mask, X rays

1 Gamma-Ray Burst Prompt Signal

First discovered in in 1967, Gamma-Ray Bursts (GRBs) are the most luminous explosions in the universe and may be detected to the highest redshift of any discrete source in the universe. These properties provide great leverage in time, wavelength and information and thus a unique opportunity to understand not only the nature of the universe but also fundamental physics[1, 2].

GRBs have been observed from space and studied extensively over the last few decades, pioneered by the *CGRO* instruments, followed by the *BeppoSAX, HETE-2,* and further improved by recent satellites such as *Integral, Swift,* and *Fermi*. In particular, *Swift* observatory has localized accurately the locations of UV/optical counterparts of hundreds of GRBs in typically 100 seconds after the gamma ray trigger, since its commencement of in-orbit measurement in 2004[3]. However, due to the inherent slow response time for slewing the whole satellite and/or ground telescopes, only a few early UV/optical light curve measurements are available. Figure 1 shows a statistics of GRBs in terms of their first detection time[4].

The typical detection method of GRB is using a X-ray or gamma ray detector to monitor the fast rising high energy photon flux and determine its direction. Then rotate the satellite to that direction to observe optical photon flux. Such satellite maneuver often takes few minutes because of large rotational inertia. Because of this drawback, the short-hard type GRBs and rapid-rising GRBs, which may account for 30% of all GRBs. This lack of early observations and the blindness to the rise phase of many GRB optical light curves along with those of other rapidly variable transient sources leaves fertile astrophysical territory. Many

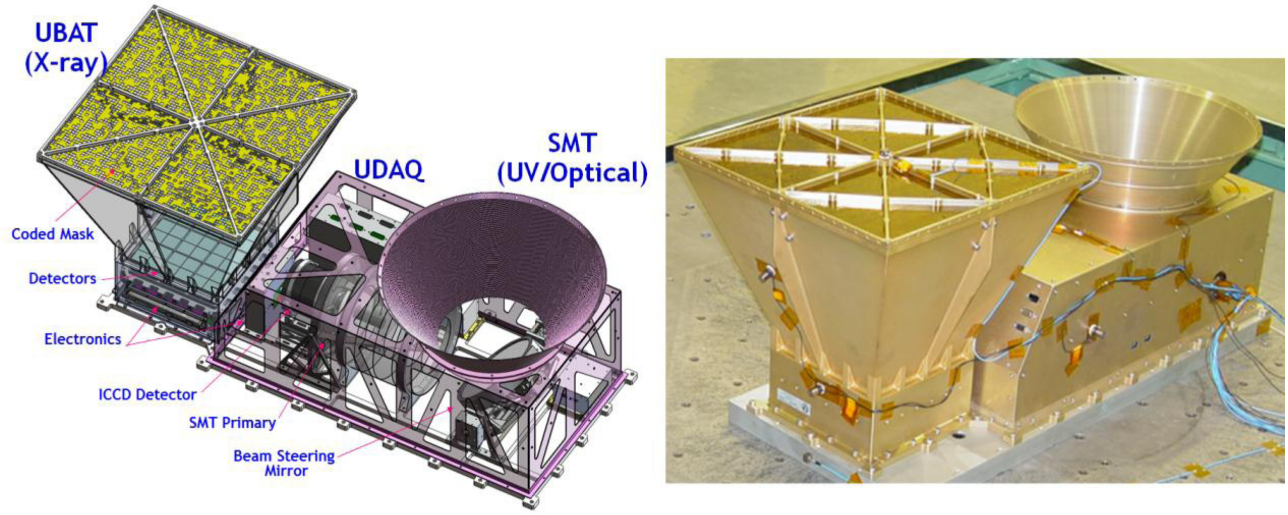

Fig. 2: A rendering of the integrated UFFO-pathfinder (left) and the fabricated flight model (right)[1].

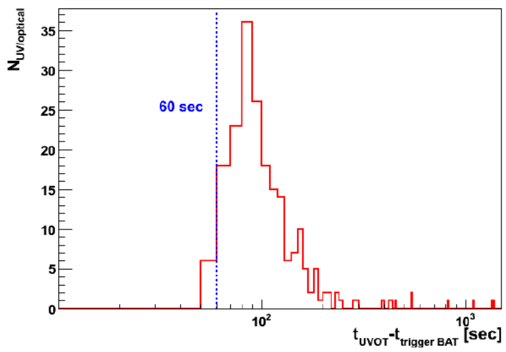

Fig. 1: The detected number of Swif's UV/optical events versus the response time of UVOT since 2005[3, 4].

important physical questions arising at the short time scales remain unexplored [1, 2].

To reach sub-minute timescales, the Ultra-Fast Flash Observatory (UFFO) uses a rapidly moving mirror to redirect the optical beam instead of slewing the entire spacecraft. The first realization of this concept is UFFO-pathfinder, shown in Figure 2 [1]. The system of the UFFO-pathfinder was designed to (i) fit the constraints of the Lomonosov spacecraft, (ii) use all pre-proven technologies and (iii) to be available for fast delivery. The main constraints for inclusion in Lomonosov are 20 kg total instrument mass, 20 Watt total power consumption, and 800 cm maximum circumference length. UFFO-pathfinder consists of two subdetectors, a fast-response Slewing Mirror Telescope (SMT) and a UFFO Burst Alert and Trigger Telescope (UBAT), together with supporting electronics, called UFFO Data Acquisition system (UDAQ).

2 Slewing Mirror Telescope (SMT)

SMT consists of three components. The slewing mirror system is built with two gimbal motors that provide 1 sec response over the entire FOV, 70×70 deg^2 with sub-arcsec positioning accuracy over the FOV and the settling time less than 350 msec. These sealed bearing motors driving gimbal-mounted mirrors are simple and robust, and turn out to be of space qualified[4].

The SMT optics includes a Ritchey-Chretien telescope with a 100mm diameter aperture. Its FOV is 17×17 arcmin^2 and f-number is 11.4. The primary and secondary mirrors were fabricated with the precision of about rms 0.02 waves in wave front error (WFE) and 84.7% in average reflectivity over 200 650 nm. The entire SMT optics was aligned with the accuracy of rms 0.05 waves in WFE at 632.8 nm. The slewing mirror is designed to 15 cm in diameter and illuminates the full aperture of the RC telescope on-axis[4].

The focal detector of SMT is an intensified charge-coupled device (ICCD) with a pixel size of 44 arcsec^2 and a wavelength sensitive to 200 650 nm. The ICCD operates in photon counting mode and could observe faint objects up to $\approx$ 19 magnitude B-star in white light per 100 s, assuming the same performance as Swift. The SMT has the readout rate of 20 ms and can take 50 frames per second[4].

The performances of the flight model of SMT including detector and readout electronics were estimated by and placing SMT in vertical direction and scanned with a He-Ne laser beam of 635 nm. The focused image is spread out to 3×3 pixels on the focal plane, producing the SMT optics PSF shown in figure 3. The 4.3 arcsec (Y-slice, Gaussian fit 1σ) PSF is the result of the quadrature sum of the possible errors such as 4arcsec ICCD PSF, 1 arcsec focal error due to gravity, and 1 arcsec error from divergence of the parallel beam. It demonstrates that the constructed flight model SMT satisfies the angular resolution requirement of 4 arsec when it operates at space environment[4].

3 UBAT

The UBAT is designed to detect X rays from GRBs within a wide FOV and determine their arrival direction. It is composed of a coded mask, a hopper, and a detector module (DM), as shown in Figure 2. The coded mask, located on top of the hopper, is an array of opaque and transparent elements of 68×68 with cell size of 5.76 mm $\times$ 5.76 mm. The mask were made from 1 mm Tungsten and two layers of Kapton tapes of 12.7μm. Such thickness allows detection of X rays in the ranges of 5 200 keV.

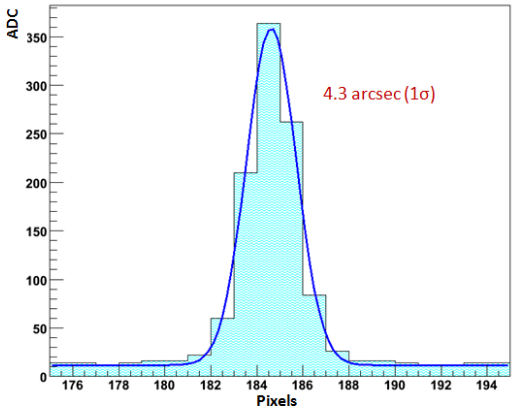

Fig. 3: A rendering of the integrated UFFO-pathfinder (left) and the fabricated flight model (right)t[4].

The hopper, situated between the coded mask and the UBAT DM structure, supports the coded mask mechanically and acts as a collimator. The DM is a 6×6 array of detector units, each consists of a 8×8 Multi-Anode photomultipliers (MAPMTs) with array of $2.65 \times 2.65 \times 2$ mm^3 YSO (Yttrium Oxyorthosilicate) scintillation crystals glued on top of front surface of MAPMT. Figure 4 shows one detector unit. Four units are attached to the several layers of electronics boards, including analogue/digital circuits, high voltage power supply, and other system control circuitries. In total, UBAT-DM has 48×48 pixel to image the GRB position. The UBAT will monitor the sky with 70.8 deg $\times$ 70.8 deg(43.2 deg $\times$ 43.2 deg) for the half-coded FOV (full-coded FOV) [5].

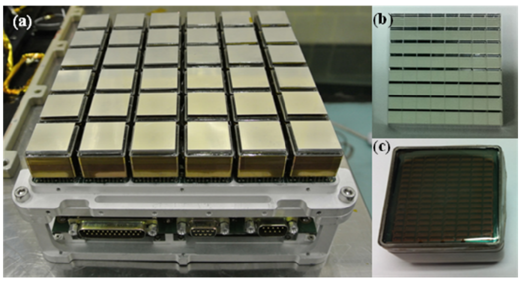

Fig. 4: (a) UBAT DM, (b) a YSO scintillator crystal array, (c) a MAPMT[5].

4 UDAQ

The UBAT trigger has two steps of the rate-trigger algorithms and the imaging algorithm. As the rate-trigger algorithm is the first step, it is to search for non-statistical variations in the UBAT detector count rate on several different timescales, in order to identify candidate GRB events. If a rate-trigger is detected, a rate-trigger flag is set which causes the imaging algorithm to reconstruct the sky image starting from a time to the onset of the trigger, by using the detector counts stored in a buffer. When the imaging algorithm reconstructs, it makes the correlation array by comparison of the detector pattern with the coded-mask pattern, and then localizes the candidate GRB events[6].

The UFFO Pathfinder has designed for the microsatellite which requires the lower limit 20 kg and 20 W for the acceptable weight and power. Therefore, the main processor chip for the UBAT trigger algorithm use the field programmable gate arrays (FPGA) not the microprocessor. The UBAT digital board there are three processing chips, which are two FPGAs and one microprocessor, and three memories, which are two SRAMs and one NOR Flash memory. One of FPGA named the Data FPGA is in charge of the UBAT readout system and another named the Trigger FPGA is in charge of the UBAT trigger algorithm.

The imaging algorithm compares the coded-mask pattern detector pattern to make the correlation image array, after then the accumulation array is made based on the correlation image. The significant single maximum or peak signal can be found from the accumulation image, and it identifies the direction of the GRB [6, 7].

5 Calibration and Simulation

The quantum efficiency and gain of all the MAPMTs used in UFFO-pathfinder are measured in Taiwan by a pulsed LED light sources. Using a variable X ray sources, we measure the photon yield of YSO crystals and theresults are shown in figure 5. The photon yueld is derived as 10.5 photons/keV and the it is linear in the test range of 22.1 keV to 59.5 keV[8].

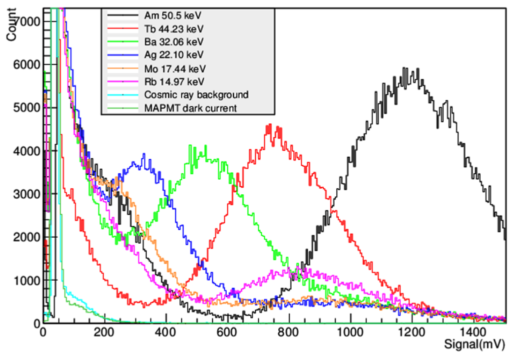

Fig. 5: The energy calibration for the YSO crystals using a variable X ray sources [8].

In order to simulate the operation of UBAT, a complete model of UBAT was constructed, using the GEANT4 simulation package. For the opening cell, the Kapton tape cuts off X rays below approximately 5 keV. For the masked cell, the Tungsten cuts off X rays below approximately 200 keV. Above 200 keV, some X ray can penetrate Tungsten mask and create a false signal[8].

Several GRB light curves are used to study the trigger time. The mean X ray count before the GRB is considered to be the background noise and counts above background are treated as a GRB signal. Simulations were performed at one frame per second and both photons from the background and/or GRB were generated independently.

Approximately 300 GRB light curves from BATSE were used in the trigger simulation. For a strong GRB, UBAT can trigger 0.5 s after the GRB starts and an additional second is required to slew the SMT. The UFFO can record optical photons as fast as 1.5 s. The exact time depends on the signal-to-noise ratio.

The angular resolutions of UBAT are studied by comparing the input direction of simulated GRB light curves and the reconstructed direction. The mean angular errors are within 17′ or 0.283° of the field of view of the SMT telescope and only a few percent of high energy photon events are outside this limit[8].

6 Conclusions

SMT has a slewing mirror to redirect optical photons into a telescope and then record them by an intensified CCD. UBAT uses coded mask to provide X-ray trigger from a GRB and provides the GRB location for SMT. UFFOs sub-minute measurements of GRBs will result in a more rigorous test of current internal shock models, probe the extremes of bulk Lorentz factors, provide the first early and detailed measurements of fast-rise GRB optical light curves, and help verify the prospect of GRB as a new standard candle.

The UFFO-pathfinder has passed space environments test, including thermal, vacuum, shock and vibrations, successfully at National Space Organization (NSPO) of Taiwan, R.O.C. in August 2011. Now, it is fully integrated with the Lomonosov satellite and is scheduled to be launched in late 2013 or early 2014.

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