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6U CubeSat for ultraviolet time-domain astronomy

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ABSTRACT

A wide-field ultraviolet observatory for time-domain astronomy utilizing 6U CubeSat is presented. Ultraviolet waveband is one of the unexplored fields in astronomy. Potential targets are short duration transient sources in UV-band: early-phase emission from gravitational wave sources, supernovae shock-breakouts, tidal disruption events around super massive blackholes, etc. The telescope was designed for covering the large error circle of GW detectors, FoV~100 deg^2. Thanks to the high quantum efficiency of “delta-doping” detector, the detection limit achieves 20 mag (AB) for 1800 s exposure in NUV band, which is sufficient to detect UV emission from a binary neutron star merger within 200 Mpc from the earth. The satellite has a high-performance on-board computer for on-orbit analysis to detect transient sources and measure the magnitude and the accurate position of the target. The obtained information is required to be transferred to the ground within 30 min from the detection to start multi-messenger follow-up observations utilizing ground-based observatories and astronomical satellites. In this presentation we show the mission overview and conceptual design of the satellite system.

INTRODUCTION

The universe is active. In this decade many astronomers have focused on short duration phenomena with a time scale shorter than ~1 day. This new field is referred to as "time-domain astronomy" and is believed to be a promising discovery space in astrophysics. The progresses of astronomy have been invoked by enlargement of aperture diameter of telescopes, because a bigger telescope can search deeper, and deeper observations can provide not only the precise measurements but also the information of the ancient universe. Therefore, a small satellite with limited payload regrettably does not have any advantages in classical astronomy. In contrast, time-domain astronomy has another evaluation axis, namely "time". In this field, a telescope is expected to detect transient phenomena earlier than ever. From this perspective, a recent high-performance small satellite can be an attractive platform on the other hand.

The new field, time-domain astronomy, has been opened up thanks to the high-speed/real-time communication (Internet), robotics technology and high-performance computing technology, and those technologies have almost eliminated human eyes and judgements from the observation work flow. Consequently, the response time of the robotic telescopes has been drastically improved. In HETE-II era (2001~2005), the typical delay in starting follow-up observation was about 60 min after gamma-ray detection on the satellite. That delay arose from the satellite communication lag and limited computational resources on satellite. Currently, we can start observation only 10 s after the Swift satellite detects gamma-rays. Recent dramatic progresses in small satellite can provide fast detection alerts from space that can be an alternative to Swift satellite with 1/100 cost.

Most of transient sources are believed related to explosive phenomena. When a huge amount of energy is released in a short period, the stellar material around the central engine is heated up to ~10^5 K and then radiates in UV light and soft X-rays. The heated material then rapidly cooled down as expands and radiates. As the apparent temperature decreases the observed color evolves redder. UV and soft X-rays are therefore ideal for detecting the prompt emission faster than the other wavelength and for investigating the very early phase behavior of transients.

In terms of detector technique, X-rays and UV are entirely different. Soft X-ray photons can be treated as particles therefore the sensor must detect every single photon individually (A photon-counting detector is required). Moreover, X-ray photons requires very special optics, such as Walter-I. On the other hand, UV photons behave similar to optical photons, which can be accumulated with usual optics and detected with Si-based semiconductor imaging devices. These properties of UV can suppress the developing cost drastically, and enables the early realization accordingly. In this paper we propose an ultra-wide field UV monitor for time-domain astronomy. In the next section we summarize mission requirements, then we show the resultant specifications of mission instruments. Considering the mission instruments, we designed satellite bus system and operation strategy.

MISSION REQUIREMENTS

Targets

Our primary targets are gravitational wave (GW) events. A binary neutron star merger GW170817 at 47 Mpc away from the earth had an electro-magnetic counterpart [1]. Couple of days after the GW detection, the emission tended to the red which is interpreted as the evidence of nucleosynthesis of heavy elements due to the neutron capture. During the very early phase the optical counterpart was rather blue so that most of scientist doubted whether the optical transient is exactly related to the GW event, or not. This blue emission seems to be originated in relativistic jet injected into the orbital axis direction [2-3]. When and how is the relativistic jet formed is one of the most mysterious open questions in the modern high energy astrophysics. The observed brightness of the EM counterpart was 18 mag in near UV (NUV) band 10 hr after the GW detection [4]. It means the required sensitivity for covering LIGO/Virgo range is 20 mag (AB) in NUV. One of the technical barriers is the large error of the position determination, typically about 100 deg^2. Therefore, we are required to survey such a large area containing millions of stars as soon as possible.

Another potential target is supernova shock-breakouts (SNSBs), precursors of supernovae. When a giant star burns out, the iron core collapses due to its own high pressure and a strong shockwave propagates from the core to the outer region. As the shockwave passes through the photosphere, the apparent temperature of the progenitor star jumps to 10^5 K in a moment due to shock-heating, and then the photosphere shines in UV band [5-6]. The luminosity and light-curve of a SNSB provide crucial information of the very final stage of the stellar evolution. Note that the UV emission of a SNSB rapidly decays with a time-scale of a couple of hours.

Moreover, there are other possible UV sources, such as tidal disruption events around super massive black holes, classical/recurrent novae, Type-Ia supernovae [7], optical flash of gamma-ray bursts, and stellar flares. Due to the technical difficulty, namely the atmospheric absorption, UV-band has not been well explored. Therefore, we can expect finding unknown phenomena. Those mission requirements are summarized in Table 1.

Table 1: Summary of mission requirements

Parameter	Requirement	Target
Wavelength	NUV (< 300 nm)	GW/SNSB
Field of View	100 deg^2	GW
Survey Area	400 deg^2	SNSB
Sensitivity (AB mag)	19 mag / orbit 20 mag / hr	SNSB GW
Cadence	1 scan / hr	SNSB
Data link	within 1 hr after detection	GW/SNSB

MISSION DESIGN

Design of mission instruments

The most critical requirement from the science mission is the coverage which arises from GW events with large position errors. To achieve ultra-wide field up to 100 deg^2, a refracting optical system is introduced. The telescope consists of 8 elements to reduce chromatic aberration and to reduce the tube length. The supporting structure of the primary lens (CaF_2) was carefully designed by GENESIA corporation based on the flight heritage in Hodoyoshi-I satellite.

As for an imaging device, we employ a delta-doping back illuminated CMOS imager. Delta-doping technique improves the charge collection efficiency just behind the back surface for UV light [8]. The detector is covered by a solar-blind AR coating which consists of 5 layer di-electric materials directly deposited on the Si wafer [9]. Those JPL's technologies enable both the high throughput ratio in UV band at maximum and the low optical leak below 1/1000 over 300~1100 nm.

We then evaluated the limiting magnitude considering the background photons originated in zodiacal light, earth shine, and geo-coronal lines. As shown in Figure 1, the expected detection limit achieves 20 mag (AB) at 5σ with a 30 min exposure. Table 2 summarizes the specification of the mission instrument.

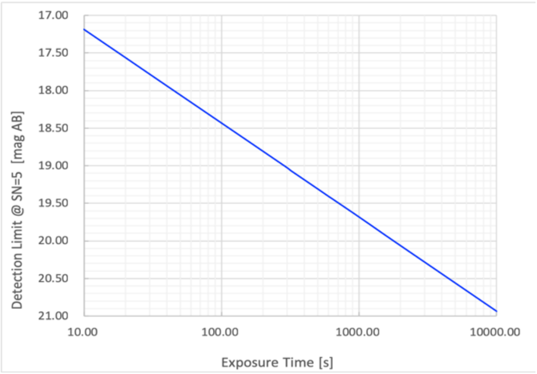

Figure 1: Expected detection limit

Table 2: Specification of Mission instruments

Parameter	Values
Wavelength	NUV (230-280 nm)
Field of View	106 deg2
Aperture Diameter	ϕ80 mm
Focal Length	267 mm (F/3.34)
Detector	Delta-doped BI-CMOS 4Kx4K
Filter	5 layer solar-blind AR coating
Pixel Scale	9.27 arcs/pix
PSF FWHM	0.98 pixel@FWHM
Dimension	H108 mm x W116 mm x L272.5 mm
Weight	2.6 kg (Telescope + Detector unit)
Flight Software	Position Determination, Aperture photometry, Transient detection, Data compression

Survey design

According to the past UV missions, UV sky in dayside is not an ideal condition for deep observation due to the earth-shine and geo-coronal lines. To achieve required sensitivity up to 20 mag, the observations must be scheduled in nightside which continues only ~30 min per orbit in LEO. Therefore, the satellite can concentrate in charging the battery and onboard data analysis in dayside. The obtained telemetry can be transferred immediately by using commercial ground stations around north polar and south polar every orbit. To avoid the earth-shine and geo-coronal lines, satellite should not be launched into a twilight orbit in which the telescope will be always suffered by the background light. Therefore, a sun-synchronous orbit with a local time of descending node around 12:00 will be ideal for this mission. In addition, we can expect to have many opportunities for the launch into such orbits which are suitable for remote sensing missions in visible light.

When we do not have GW alerts, the satellite starts the basic survey to sweep 400 deg^2 per orbit. Each pointing of 100 deg^2 has 5~ min exposure which leads to 19 mag (AB) at 5σ. The satellite maneuver to the adjacent pointing should be less than a minute to maximize observation efficiency. The satellite comes back to the same sky field in the next orbit and repeats the observation. The exact cadence is subject to change due to the orbit trajectories, but if the satellite is launched into a LEO, then it can produce 15–16 data points per pointing with a 96 min cadence. The 400 deg^2 field is monitored for 3 weeks and move on to the next field. Consequently, the satellite will monitor 17 field per year which corresponds to 6800 deg^2. Figure 2 describes the schematic view of the basic survey operation in an orbit.

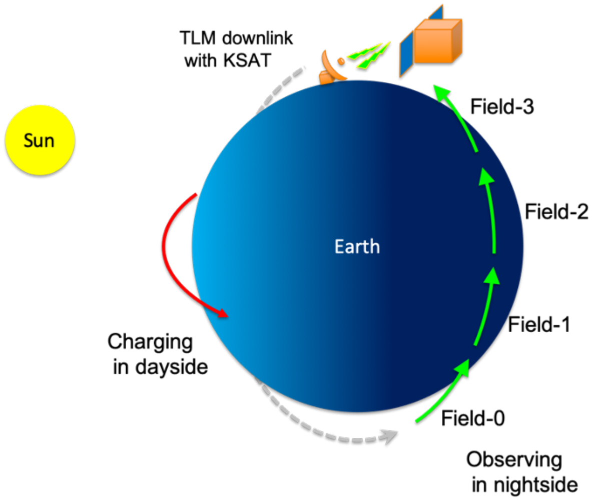

Figure 2: Schematic view of the basic survey.

Expected event rate

Table 3 summarizes the expected event rates of this UV mission considering the performance of instruments and survey efficiency described above.

The event rate of NS-NS merger is still unclear but our telescope can detect early blue emission from GW sources assumimg the same luminosity observed in GW170817[4]. LIGO/Virgo detected another NS-NS merger ~300 Mpc away in 2019. This means that GW170817 was not a lucky punch. We must prepare for the next NS-NS merger as soon as possible. We also estimated the event rate of core collapse SNe. The apparent luminosity strongly depends on the mass loss rate in the final decade just before the core-collapse. The low mass-loss star will be dimmer because the apparent size at the shock breakout is small. Therefore, the expected event rate becomes lower. In case of high mass-loss case, the apparent luminosity will be much brighter. The expected event rate will be 25 events/yr. A statistical study of the stellar wind activity in the very final stage is quite unique and essential to understand the stellar evolution. In addition, we have several intriguing potential candidates of UV transients including unknown sources, therefore many researchers are looking forward to observation.

Table 3: Expected event rates.

Target	Event rate for this satellite
GWs (NS-NS)	0.4~16 events/year
SNSB at photosphere SNSB with dens wind	~1 events/year ~25 events/year
Tidal Disruption Event	~2 events/year
Type-Ia SN Early Rise	~1 events/year
Classical/Recurrent novae	a few events/year

SYSTEM DESIGN

System Requirements

Table 4 summarizes the system requirements from the mission. A remarkable requirement is attitude stability better than ~10 arcsec during exposure time. In astronomical observation, a long exposure time up to hundred seconds is required to detect faint objects. During the exposure time the aim point of the telescope must be point the same direction at an accuracy of the pixel scale of the detector. Fortunately, Christopher et al. [5] reported excellent demonstrations of attitude control system aboard a 6U CubeSat ASTERIA, and our requirement is much easier than that.

The other technical issue to be concerned is temperature control of mission equipment. The dominant noise source of the detector system is the dark current even at -20˚C. For this issue, we will develop a thermoelectric cooling system and a heat panel mounted on the satellite surface. Another thermal issue is the temperature dependence of focal length of the telescope. The telescope consists of CaF_2 and fused silica is quite sensitive to the temperature variation. Although we developed a focusing mechanism, the temperature of the optical tube must be stable in range of ±1˚C during an exposure.

The final issue to be concern is the RF communication system. As described in the introduction, time-domain astronomy requires huge amount of data. The estimated data rate reaches into 2 GB/day. We therefore decided to employ a commercially available high-performance X-band transmitter to transfer the obtained UV images. In addition, commercial ground station service can be utilized. The daily downlink operations are incredibly hard work for a small satellite project in universities. We take advantage of commercial services proactively for the science goals.

Table 4: System Requirements.

Parameter	Values
Payload size	3 U / 3 kg
Power Supply	10 W @ Maximum
Attitude Stability Pointing accuracy	~10 arcsec @ 1σ ~ 1 arcmin
Temperature Control	Detector Temp.: < -20˚C with TEC Temp. Stability of Telescope: ±1˚C
Data Rate	2 GByte /day
Data Delay	Alert: < 30 min Telemetry: < 3 hr

System design

Figure 3 describes the system block diagram. Colors of components indicate the development status. Right-side of the figure describes the functional block of satellite bus system, which consists of commercially available and already demonstrated components for avoiding accidents and troubles. The design concept of this project is "reducing developing efforts for satellite bus system", which based on our lessens and learns from the previous satellite project [11]. Therefore, we can concentrate in developing the mission specific components.

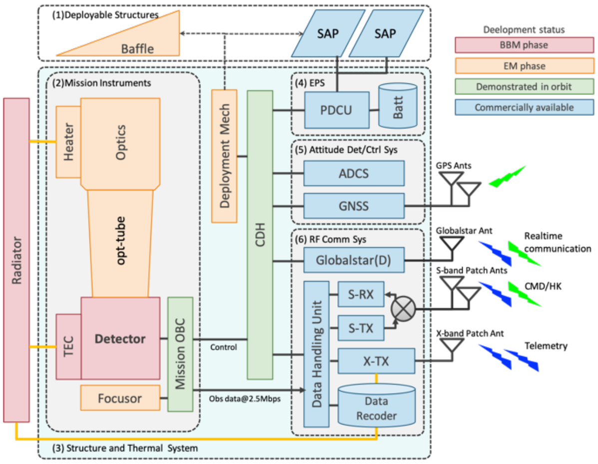

Figure 3: System block diagram.

Table 5 summarizes the resultant specification of the satellite bus system. The power consumption of the satellite is around ~22 W in the normal operation (the basic survey mode). The peak power demand of ~40 W occurs for the TLM downlink operation with a duration of ~10 min/orbit. The required power generation is 36 W, requires more than ~48 solar cells. The battery capacity will be larger than 80 Wh for feeding mission instruments in nightside.

We are still discussing the size of satellite structure. The temperature condition of the payload is one of the mission critical issues. In general, the thermal design with larger bus is easier, although we also understand the difficulty of 30 kg bus [11]. The first thing we should do is developing an engineering model of the mission component for enabling accurate thermal-structural analysis.

Figure 4 describes component layout for a 6U bus. If we do not consider the thermal design, all of the components can be packed in to the standard 6U bus. The total mass of the satellite will be around 11 kg.

Table 5: Specification of Satellite Bus system.

Parameters	6U case	30 kg case
Weight	11 kg	~30 kg
Power Consumption	22.2 W@nominal (40.2 W@maximum)	
EPS	Power generation: 36 W @ EOL Battery capacity: 80 Wh @ EOL	
ADCS	3-axis non-bias stabilized Stability: 10 arcsec@1σ during 100s Slew speed: 1 min for 20° MNV	
Orbit	Alt 500 km Sun synchronous orbit	
Communication	CMD: S-band (Up 4 kbps/Down 1Mbps) TLM: X-band (Down 10 Mbps) ALERT: Globalstar (700 Byte/access)	
Ground Station	S-band: ISAS/JAXA, Singapore (MIT) X-band: KSAT stations (6 pass/day)	
Data pipeline	Data server: itch/Univ Tokyo Broadcast: GRB Coordinate Network	
Mission Life	2 years	
Launch	~2023	

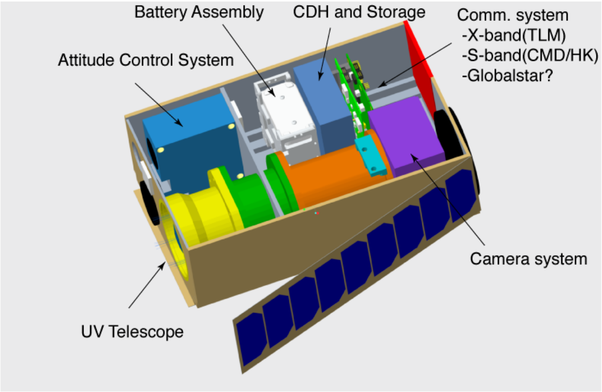

Figure 4: Component layout for 6U CubeSat Bus.

CONCLUSION

We argued the conceptual design of the small satellite for ultraviolet time-domain astronomy. The mission goal is detecting UV counterparts of GW sources, supernova shock breakouts, tidal-disruption events, UV flashes from type-Ia supernovae, UV emission from classical/recurrent novae and completely unknown phenomena. In addition, we realize worldwide multi-messenger follow-up observations collaborating with ground-based telescopes prompted by the UV observation. To surely attain the success criteria, the satellite bus is designed with commercially available components, and we eliminated inessential technical challenges in designing satellite bus system. This design concept also enables early realization of the flight in 2023.

Acknowledgments

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