Micro-satellite for Astrometry and Photometry of Gravitational Wave Sources

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Abstract

We propose a micro-satellite for surveying EM counterparts of gravitational wave sources and the time-domain astronomy in ultraviolet. Several theoretical study predicts NS-NS mergers may produce strong UV emission prior to the optical and IR emission. If that is the case wide-field UV monitor is useful for detection and position determination of EM counterparts. For this purpose we designed a ϕ200mm reflector and a satellite bus for this mission. The expected limiting magnitude is $\sim$22 mag$_{AB}$ in the 200$-$300 nm band for 300s exposure. Cooperate with the agile satellite bus system, this satellite system can survey 100 deg^2 with a cadence of 2 cycle h^{-1}. With an assuming of UV emission from free-neutron decay, more than one NS-NS merger can be detected with the system.

Key words: Ultraviolet, Time-domain astronomy, Gravitational Wave, Micro-satellite

1. Introduction

In 2015, the first gravitational wave (GW) event in human history was finally detected. The astronomers are now aiming for detecting the electromagnetic counterparts of GW events. The technical barrier to be overcome is the large error circle of the GW telescopes, typically larger than $\sim$100 deg^2. Therefore the prompt and accurate position determination is the necessary step towards the multi-messenger astronomy in the GW-era.

Table 1. Mission Requirements

Parameter	Requirement
Band.......	200$\sim$300 nm
Detection limit.......	$\geq$22 mag$_{AB}$
Time span.......	$\sim$ 1 hour
Survey area.......	$\geq$ 100 degree^2
Cadence.......	$\geq$ 2 cycle hr^{-1}
Delay of Alerts.......	$\leq$ 30 min
Detection rate.......	$\geq$ 1 event yr^{-1}

2. Target Profile

The first GW event seemed to be generated by a binary black-hole that believed not to produce any radiation. Therefore we expect neutron star (NS)-NS mergers which produce r-nuclei and these radioactive ejecta result in the kilo-novae. The nature of the kilo-novae is still unclear and numerous theoretical models are proposed. Part of the claimed that free neutrons in the outer edge of ejecta produce ultraviolet photons due to the beta-decay(Brian D. Metzger et al. 2015).

In this scenario, as the emitting region is exposed the luminosity is should be higher and prior to optical/IR photons which experienced scatterings and absorption in the optical thick r-nuclei. Fig. 1 shows the simulated light curves in various colors of a kilo-novae at 200 Mpc from the earth. The bluer the peak flux is higher, 22 mag$_{AB}$ in U-band. The rise time is about 1 hour which is shorter than that of the typical kilonovae model (no neutron heating model) by factor of 1/10.

If that is the case, ultraviolet which is brighter and faster than the other colors can be the best way to detect and determine the position of the GW source. Moreover the its light curve has crucial information for constraint the physical state of the condensed matter in neutron star, i.e. the equation of states, the r-process nucleo synthesis.

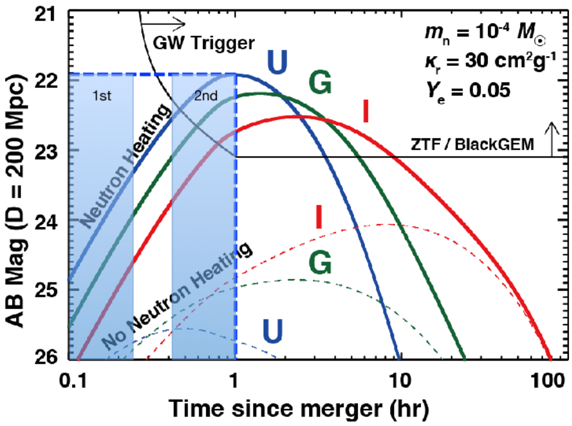

Fig. 1. Simulated light curves a NS-NS merger from Brian D. Metzger et al. (2015).

3. Mission Requirements & Design

Based on the target profile shown in the previous section, the mission requirements are summarized in table 1. It is difficult to transfer all the data to the ground instantly, we must analyze the raw-data and detect transient source on-board. In this case, two images taken at the different time epoch is required to compare the luminosity of the candidates. If we start the observation just after the GW detection, we must take more than two images before the maximum. This result in the lower limit of

$$[\text{Num of tiling}]\times[\text{FoV}]\times[\text{Cadence}] \geq 200\ \text{deg}^2\text{hr}^{-1}. \quad (1)$$

While the payload size is strictly limited by the piggy-back regulation of the H-IIA launching vehicle. The maximum diameter of the telescope is ϕ200 mm that requires the minimum exposure time of 300 s to detect 22 mag_{AB}. Therefore the field of view of the telescope system should be larger than 17 deg^2. To satisfy the requirements and that can be put into the satellite bus, we employed the Riccaldi-Honders optical system.

As the ultraviolet imager to be coupled with the telescope, we employed a back-illuminated CCD developed by Caltech for UV survey missions. The CCD has large physical format of 31 × 31 mm^2 and high Q.E. $\geq$ 80%. That fulfill the our mission requirements. The specifications of the detector systems are summarized in Table 2.

4. System Design

The above mission strategy requires both high-speed and quite stable attitude control system. For this mission we are developing a novel attitude control method, namely *Variable Structure Attitude Control; VSAC* (Kyosuke Tawara, and Saburo Matunaga 2015) which utilizes the anti-torque generated by swinging the appendages, such as the solar array paddles. For this purpose Hibari has four 400mm x 400mm solar array paddles mounted on the end of 400mm long arms and these arms are driven by motors via reducing gears. Remarkably this method enables rapid maneuver faster than 10 deg s^{-}1 whilst maintaining attitude stability higher than 15 arcsec s^{-}1. In addition, it does not requires additional space and mass for the actuator as is for control moment gyroscopes (CMGs) but only motors and small electrical power. Therefore this method can be valuable especially for the sophisticated missions on micro-satellites with critical limitations in power, weight and space.

Thanks to the VSAC which effectively utilizes the limited resource, the satellite bus is fall within the criterion of 50×50×50 cm^3. In addition the power consumption of the satellite is below 50 W, which is about 50 % of our previous 50 kg-satellite with CMGs. The science mission also requires real time RF communication for following-up GW events and broadcasting detection alerts to the ground. For this purpose we employ the Iridium network. This shrinks the delay of both up/down-links within 30min on average. With this satellite, more than one UV counterparts of GW sources and a few tens of core-collapse supernovae and the other unknown phenomena can be detected per year.

Table 2. Specifications of the Detector System

Parameter	Value
Diameter.......	200 mm
Focal length.......	430 mm
Field of view.......	17 deg^2
UV Transmittance.......	70 %
PSF.......	15 arcsec (FWHM)
CCD size.......	31 mm × 31 mm
pixel number.......	2064 × 2064 pix
Quantum efficiency.......	60 ∼ 80 %@200∼300 nm
Dark current.......	8.3 $e^{-}s^{-1}pix^{-1}$ @ −30°C

Table 3. System Requirements

Parameter	Required	Designed
Attitude stability	15 arcsec / 10s	>15arcsec /10s
Slew speed	≥1 deg s^{-1}	8 deg s^{-1}
Visible Area	0∼ 40deg	0∼40 deg†
Power supply	96 W	120 W @ EOL
Data rate	30 MB day^{-1}	36 MB/day^{-1}

†: angle from the anti-sun direction.

References

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