# Optical wide field monitor AROMA-W using multiple digital single-lens reflex cameras

I. Takahashi,[1] K. Tsunashima,[1] T. Takeda,[1] S. Ono,[1] K. Yamaoka,[1] A. Yoshida,[1]

[1] Department of Physics and Mathematics, Aoyama Gakuin University, 5-10-1 Fuchinobe, Chuo-ku, Sagamihara, Kanagawa 252-5258, Japan.
[1] Institute and its address of author1 and author2
*E-mail(IT): itakahashi@phys.aoyama.ac.jp*

Abstract

We are developing and operating the automatic optical observation device Aoyama Gakuin University Robotic Optical Monitor for Astrophysical objects - Wide field (AROMA-W). It covers a large field of view of about 45 °× 30° degrees simultaneously by using multiple digital single-lens reflex cameras, and provides photometric data in four bands with a limiting V magnitude of about 12-13 magnitude for 100 seconds exposure with $3\sigma$ threshold. The automatic analysis pipeline which can analyze data in parallel with observation has been constructed so far. It produces the light curves of all stars in the field of view of AROMA-W. We are aiming at the simultaneous observation of the transients (e.g., X-ray nova, Supernova, GRB) that MAXI discovered by using AROMA-W. We report the developmental status, the observational results of AROMA-W.

Key words: Optical, Transients, DSLR

## 1. Introduction

Monitor of All-sky X-Ray Image (MAXI) can monitor X-ray variabilities and spectra of various X-Ray transients. Among them, there are objects that have been observed not only in X-ray but also in optical band. Supernovae and novae are surveyed by various telescopes, and have increased the number of discoveries every year. Some Gamma-Ray Bursts (GRBs) are bright in optical (Van Paradijs, J. et al. 1997). In GRB 080319B, the brightest prompt optical emission that peaked at a visual magnitude of 5.3 was discovered during the burst (Racusin, J. L. et al. 2008). As for these phenomena, we cannot easily predict when and where they occur. To observe them before the onset, it is necessary to monitor the sky with a wide field of view and a high observational efficiency. Today these wide field cameras, utilizing CCDs and the commercial camera lenses, designed for this purpose have been established and are already in operations (e.g. WIDGET (Urata, Y. et al. 2011), Pi of the sky (Małek, K. et al. 2010), MASTAR-VWF (Gorbovskoy, Evgeny et al. 2010), RAPTOR Q (Woźniak, P. R. et al. 2009)). However these observational equipments are very expensive, so that we are developing a low cost wide field observation device - *Aoyama Gakuin University Robotic Optical Monitor for Astrophysical objects - Wide field* (AROMA-W) that utilizes multiple digital single-lens reflex cameras (DSLRs). AROMA-W would be a good partner for MAXI. AROMA-W monitors usual variable stars, comets and meteors besides optical transients (OTs) by wide field of view. Figure 1 shows a photograph of AROMA-W. The development and the performance of AROMA-W are described in the following sections.

## 2. Hardware

AROMA-W is set up in Sagamihara Campus of Aoyama Gakuin University (Latitude = 35.566° and Longitude = 139.403°). The development of AROMA-W is under way since 2005. Currently 12 cameras are functioning semi-autonomously. The composition equipment and the control techniques of AROMA-W are explained in the following subsections.

### 2.1. Equipments

AROMA-W consists of multiple consumer DSLRs on an equatorial mount. In September 2010, we increased the number of cameras. Currently two Canon EOS 5D with a EF200mm F2.8 and ten EOS 350Ds (EOS D Rebels) with EF100mm F2.0 USMs are used. Because their market prices are about of 1/10 compared with cooled CCD cameras for astronomical purpose, so that we can prepare a number of backup instruments. As a result, they can be easily exchanged without a loss of the observation time even when they suffered from troubles in system such as a shutter failure. German equatorial mount with

Fig. 1. AROMA-W.

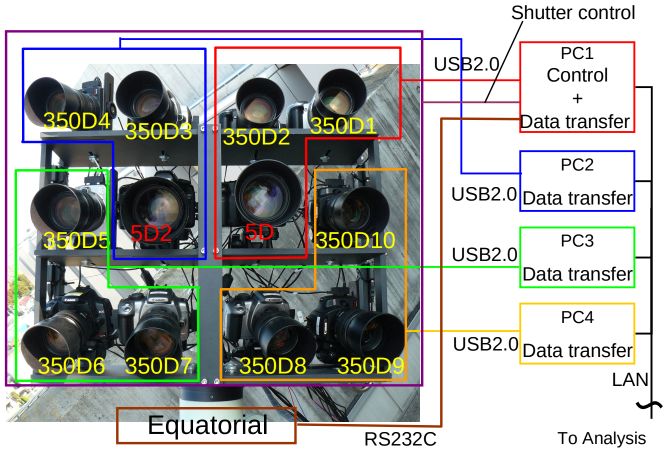


Fig. 2. The schematic diagram of the AROMA-W system. Each camera and the equatorial telescope are controlled by PC1. The observational data are acquired individually by the four PCs and forwarded to an analysis machine through LAN.

built-in two axis motors(Takahashi EM-400Temma2) is used for the equatorial mount.

### 2.2. Control technique

AROMA-W is remotely controlled through LAN. Figure 2 shows the schematic view of the AROMA-W observational system. There are 4 PCs for controlling instruments and data taking. Each PC handle data taking from 3 cameras by every frame via USB2.0. The camera shutters are controlled by the pulse from the DIO board in the PC so that the exposure of each camera is synchronized. The acquired data are sent to analysis PC via LAN in frame by frame. The dead time between frames can be shortened at 3-4 seconds because the data transfer and the exposure are done at the same time. The remote control of the equatorial mount is also possible, in the nominal mode it currently follows the view of BAT/*Swift*.

## 3. Software

AROMA-W data are analyzed by auto analysis pipeline which is described in the following subsections.

### 3.1. Auto analysis pipeline

Analysis processes are automated, and run in parallel with the observation. Figure 3 shows the schematic diagram of the real-time analysis pipeline. First, AROMA-W data are transmitted from Compact Flash memorys (CFs) in the DSLRs to the analysis PCs via the transfer PCs. Then the image processing starts. The RAW data are converted to FITS, and then the data reduction is processed; subtracting dark noise and correction of flat pattern, after those, resolving data into tri-colors and positional corrections are performed. Next, the main analysis starts; detection of astronomical objects and comparison with star catalogs (mainly USNO B1.0) are processed. By comparing photometry data, light curves of magnitude and flux ratio are obtained for all the objects within the AROMA-W FOV. By monitoring light curves continuously, variable stars and transient objects (GRB, SNe, X-ray novae etc.) will be detected. Furthermore an unexpected brightening and variability may also be detectable.

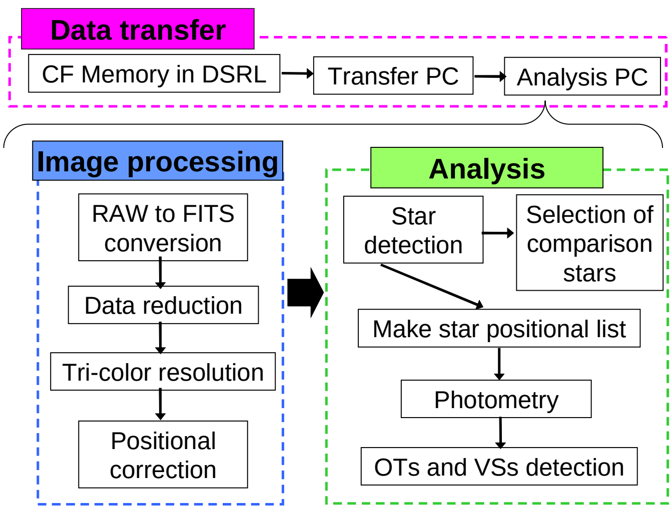


Fig. 3. The schematic diagram of the real-time analysis pipeline.

### 3.2. Tri-color resolution

The optical filters are placed on the image sensor of a DSLR along with a Bayer arrangement which has an alternating arrangement of three primary color, i.e., red, green and blue (here we call R', G' and B') (B. E. Bayer. 1976). Simultaneous multiple-band observations are achieved by reading the data for these filters individually (Tri-color imaging). *W band* data which represents brightness information is obtained by adding the three colors data. Since the digital cameras employs R', G' and B' filters which are slightly different from the standard system (R, V and B), the relation between our filter system and the standard system has been investigated by observing the same objects with various magnitude ranges simultaneously, the magnitude relations (i.e., R-R', V-G' and B-B') are obtained. For example, the relations for EOS 5D are well fitted by a linear function; R = (0.88±0.02)R'−(3.1±0.3), B = (0.93±0.02)B'−(0.2± 0.3) and V = (0.90 ± 0.01)G'−(2.8 ± 0.2), where the quoted errors are 68.3% confidence levels. 350D also has a similar linearity. The standard system photometry with DSLRs can be made by correcting them applying these linear relationship. Figure 4 show the schematic diagram of the Tri-color imaging.

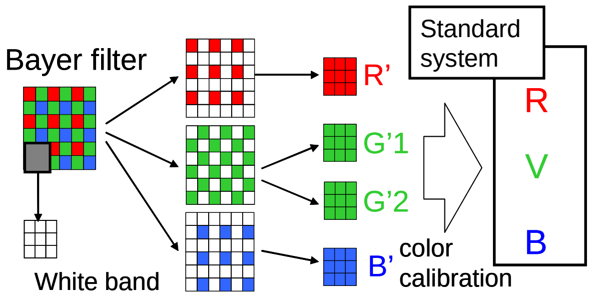


Fig. 4. The schematic diagram of the Tri-color imaging. Red, two green and blue filters are placed along with a bayer arrangement on the image sensor. The W band image is made by adding the four images.

### 3.3. OTs and VSs detection

Brightening OTs and fading stars can be searched by comparing photometric data of detected stars in the previous frame. The variability of each light curve is investigated at a certain interval, and if it exceeds a certain threshold, it is recorded and/or triggers an alert.

#### 3.3.1. OTs

In the analysis phase, object positional list is updated frame by frame. We search brightening OT by comparing current list and new one. Sudden fading objects also can be found by comparing of the lists.

#### 3.3.2. Meteors

The algorithm that detects line objects and artificial materials is being developed. It will become possible to detect meteors, tracks of satellites and aircrafts.

#### 3.3.3. Variable Stars

The pipeline update maximum and minimum averaged flux ratio of all objects in every $N$ frames (The number $N$ can be changed). The light curve is made and investigated with a variable time scale so that variable star with various periods can be detectable. Moreover, by consecutively updating minimum and maximum values, it is made possible to detect the maximum optical amplitude of a variable star and to improve its detection sensitivity.

## 4. Observational Performance

An unique feature of AROMA-W is to combine a number of commercial DSLRs and to survey continuously a large sky area. The limiting magnitude, the magnitude accuracy and field of view are described in the following subsections.

### 4.1. Limiting magnitude

The limiting magnitudes of each filter were investigated for all digital cameras. The sky background condition of the AROMA site is not very good. The $3\sigma$ limiting magnitudes of EOS 5D (20 s exposure taken in relatively good sky condition) are R = 12.1, V = 12.8 and B =13.5. Those of 350D are R = 11.9, V = 12.3 and B =13.4. Figure 5 shows the summary of W band limiting magnitude with 5D and 350D. This implies that our new system can detect GRB optical flashes like GRB 990123 with $\sim$ 9 magnitude (Akerlof, C. et al. 1999) and GRB 080319B with $\sim$ 5.3 magnitude. It is known that supernovae can be very bright in optical and X-ray band. Since the time scale of their decay is tens of days, and the optical peak is about 12∼13 mag (V band), AROMA-W can detect such a peak with a few minutes exposure. Some X-ray novae also can be detected with the sensitivity of AROMA-W. Generally, after an X-ray nova is detected with X-ray detectors, observations in the optical band are conducted. If an extensively large FOV monitor observation, such as those possibly by AROMA-W, is running during almost all the night, a detection in optical could be made in advance of its onset in X-rays.

### 4.2. Magnitude correction

As explained in subsection 3.2, observed magnitude and catalog magnitude can be corrected by a simple, linear function. Figure 6 shows a graph where the corrected observation magnitudes of the objects are compared with the catalog magnitudes of USNO B1.0 in the case of EOS 5D+200mm F2.8 lens, R band and 200 seconds exposure.

### 4.3. Field of View

The large field of view (FOV) of AROMA-W consists of that of the multiple cameras to make a mosaic image. An EOS 5D with a EF200mm F2.8 USM has a FOV of

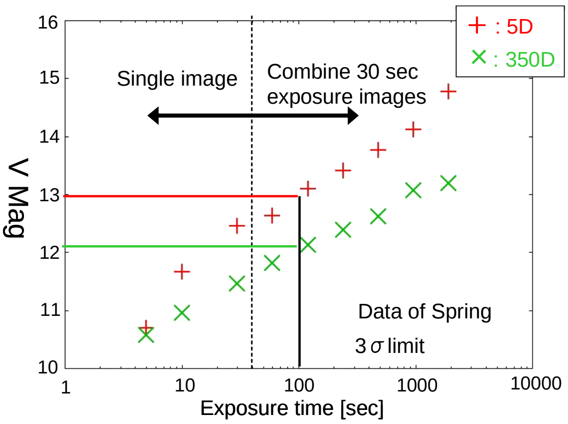


Fig. 5. The summary of V band $3\sigma$ limiting magnitude with 5D and 350D in spring. We used data that had combined the frames of the 30 seconds exposures about the exposures of 60 seconds or more. There is a difference of about one magnitude in V band between 5D and 350D.

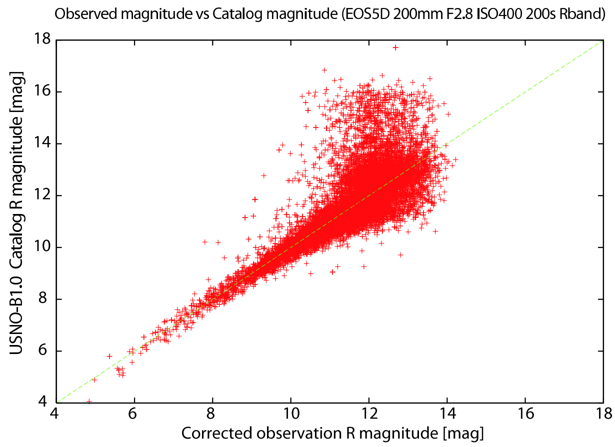


Fig. 6. The correlation diagram of catalog magnitude and corrected observation magnitude in the case of EOS 5D+200mm F2.8 lens, R band and 200 seconds exposure. The green dotted line shows $y = x$. The correlativity is weak around the limiting magnitude.

10.2°×6.8°, and a 350D with a EF200mm F2.8 USM has that of 13° × 9 °. By having increased the number of cameras in 2010, the FOV of AROMA-W has extended from 35° × 25 ° to 45° × 30 ° with twelve cameras. Figure 7 shows an image taken by the AROMA-W FOV. The views of the 5Ds are arranged at the center, and the views of 350D are arranged in the surroundings.

## 5. Observational Results

By the real-time analysis pipeline, its equatorial coordinate and observation time in MJD are automatically recorded for each frame. These functions enable to make long-term light curves of specific coordinates easily. To check whether the long-term light curve was made correctly or not, we monitored already-known variable stars. Some dozens of already-known variable stars were detected, and it was confirmed that the long-term light curves were consistent with those of the catalog period. Figure 8 shows light curve examples of detected variable stars which were detected by the real-time analysis.

## 6. Conclusion

In order to observe OTs such as associated with GRBs, SNe, X-Ray novae, we are developing and operating AROMA-W; the full-time wide-field observation system using multiple DSLRs. The AROMA-W hardware can be remotely controlled, and an automatic analysis is done in real time. FOV of AROMA-W is 45°×30°, and its limiting magnitude is V12∼13 for 100 sec exposure. The Table 1 shows the comparison with other experiments about the above-mentioned performance. AROMA-W has a performance comparable to other *much expensive* experiments. The detectability of a number of already-known VSs has been confirmed, and their long-term light curves are consistent with those of catalogs. The collaboration with MAXI is to be continued.


## Acknowledgement

This work was supported in part by the Sasakawa Scientific Research Grant from The Japan Science Society (Grant No.22-219).


## References


Van Paradijs, J. et al. 1997 *Nature*, **386**, 686–689

Racusin, J. L. et al. 2008 *Nature*, **455**,183–188

Urata, Y. et al. 2011 *PASJ*, **63**, 137–146

Małek, K. et al. 2010, *Advances in Astronomy*, **2010**, Article ID 194946

Gorbovskoy, Evgeny et al. 2010, *Advances in Astronomy*, **2010**, Article ID 917584

Woźniak, P. R. et al. 2009, *ApJ*, **691**,495-

B. E. Bayer. U.S. Patent no. 3,971,065. July 1976.

Akerlof, C. et al. 1999, *Nature*, **398**, 398–400

Vestrand, W. T. et al. 2002, *SPIE*, **4845**, 126–136

Beskin, Grigory et al. 2010, *Advances in Astronomy*, **2010**, Article ID 171569

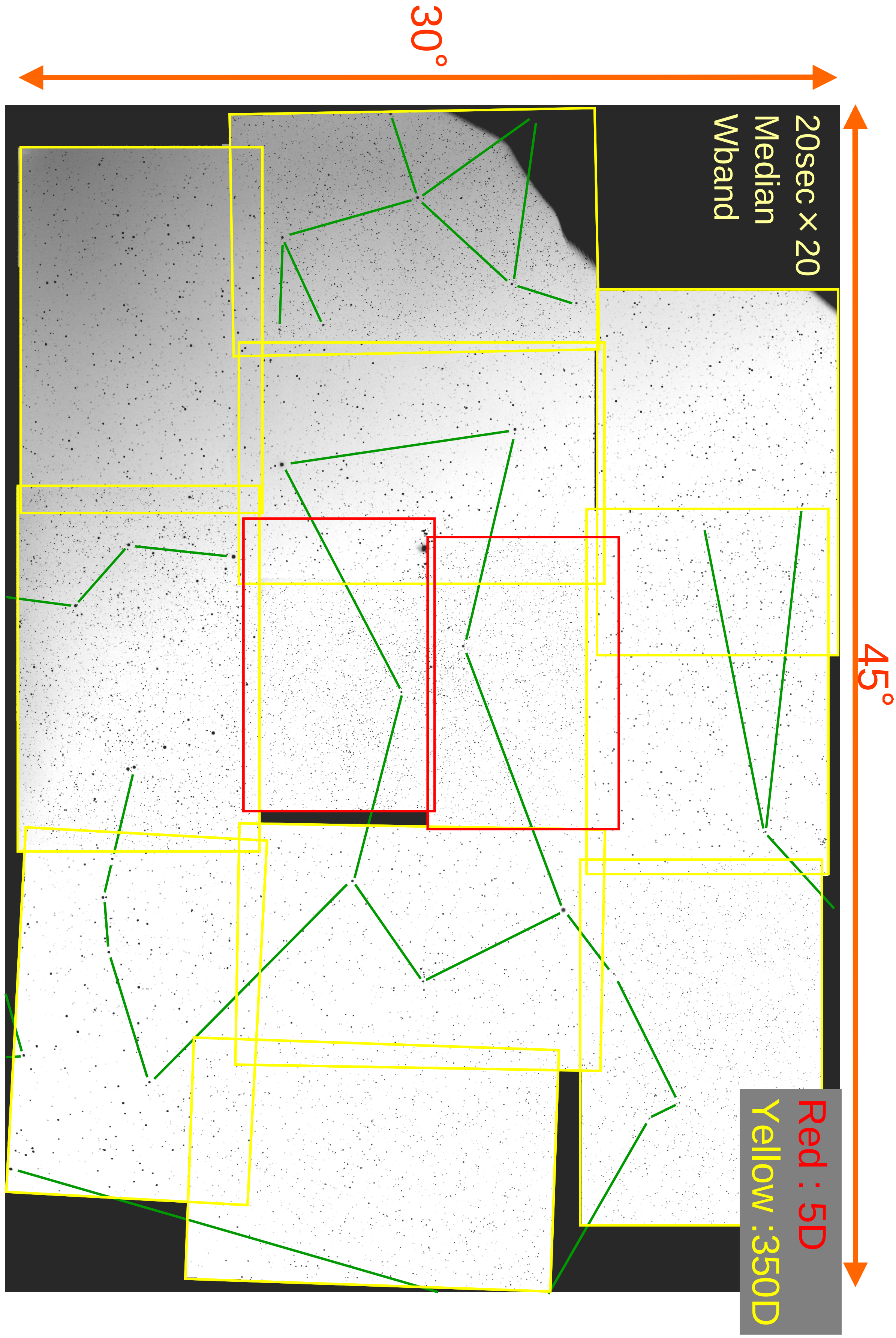


Fig. 7. The AROMA-W field of view. This is a combined image of 20 frames of W band exposed for 20 s in the vicinity of Orion. The mosaic image shows the data taken by all twelve cameras, in which the red rectangle displays the FOV of 5D and the yellow FOVs of 350Ds. This image contains about 20 thousand objects ($3\sigma$).

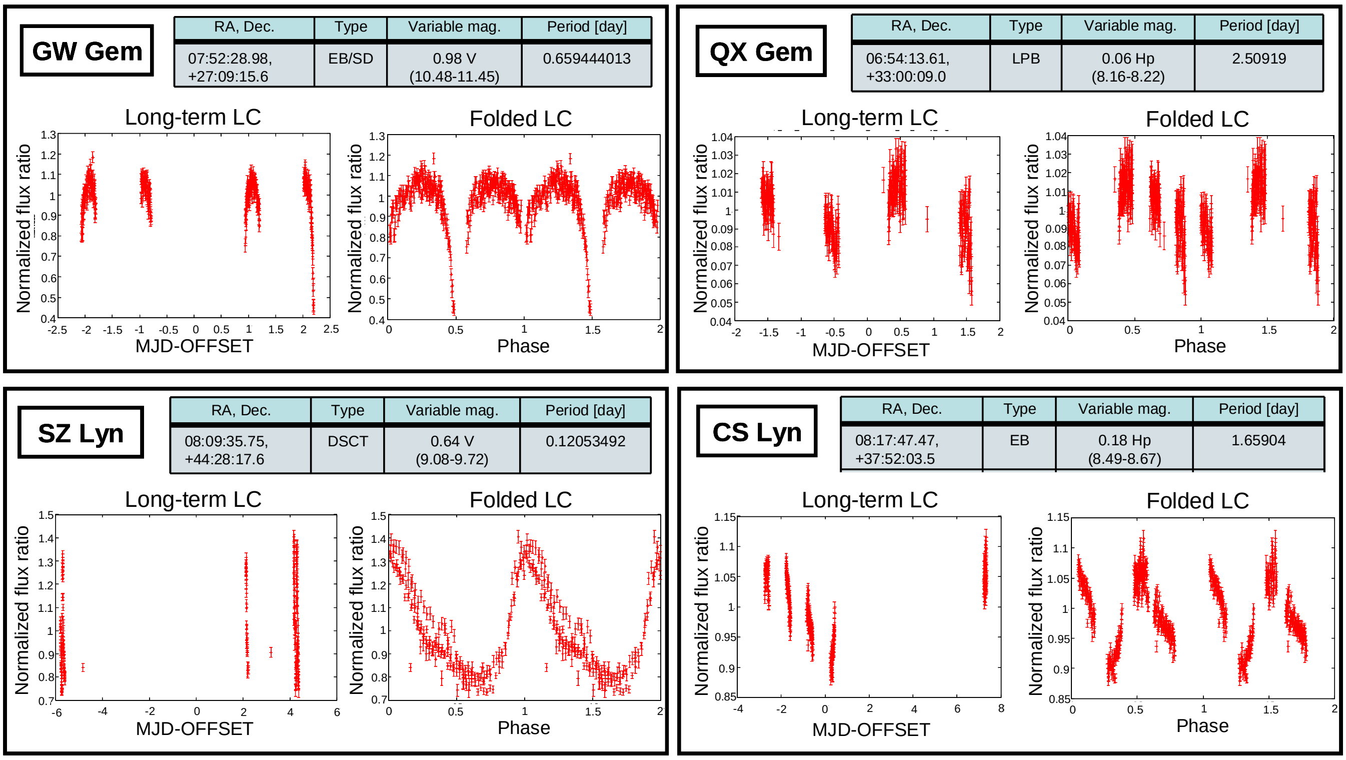


Fig. 8. Light curve examples of detected variable stars which were detected by the real-time analysis. These are the long-term light curves and the folded light curves at each period.

Table 1. Comparison of the observational performance.The limiting magnitudes are typical values, and change by sky condition.

| Experiments | System | FOV | Exposure [s] | Limiting magnitude [mag(V)] | Reference |
|---|---|---|---|---|---|
| MASTER-VWF | CCD | $4\times28°\times42°$ | 0.3-10 | 11.5 (5 s) 9.5 (0.3 s) | Gorbovskoy, Evgeny et al. 2010 |
| Pi of the Sky | CCD | $2\times16\times22°\times22°$ | 5-10 | 12 | Małek, K. et al. 2010 |
| RAPTOR A/B | CCD | 1500 square degrees | 60 | 12 | Vestrand, W. T. et al. 2002 |
| RAPTOR Q | CCD | $180°\times180°$ | - | 10 | Woźniak, P. R. et al. 2009 |
| TORTORA | TV-CCD | $24°\times32°$ | 0.13 | 9-10.5($3\sigma$) | Beskin, Grigory et al. 2010 |
| WIDGET | CCD | $4\times32°\times32°$ | 5 | 11 | Urata, Y. et al. 2011 |
| AROMA-W | DSLR | $45°\times30°$ | 20 | 11.5(350D), 12.5(5D), ($3\sigma$) | - |