東京大学木曾観測所超広視野高速CMOSカメラ
Tomo-eの開発

酒向 重行
(Institute of Astronomy, the University of Tokyo)
and
the Tomo-e Gozen project team:
次の時代、国内、可視光、口径1m、シーイング4秒角、で、何ができると言うのか？
間違いなく言えること、後追いでは、勝てない。
Outline

- Overview of Kiso wide-field CMOS camera, Tomo-e
- Development of Tomo-e
- New science capability with Tomo-e
Kiso Observatory

- Established in 1974
- Open use operation
- Dark sky, 1,120m altitude
- Accommodation, Cafeteria
Kiso 105 cm Schmidt Telescope

Extremely wide field telescope

- Field of view: $\phi$ 9 degrees
- Primary: 150 cm spherical mirror
- Corrector: 105 cm aperture
- Focal ratio: 3.1

Photographic plate
(36 cm x 36 cm)
used until the 1990s
KWFC: Kiso Wide Field Camera

- 8 CCD chips with 8k x 8k pixels
- F.O.V of 4.8 deg² (2.2 deg. x 2.2 deg).
- Open use operation started in April 2012
- **Fully automatic observation system using queue lists**

<table>
<thead>
<tr>
<th>Pixel scale</th>
<th>0.946 arcsec/pix</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCDs</td>
<td>2k x 4k MIT x 4</td>
</tr>
<tr>
<td></td>
<td>2k x 4k SITe x 4</td>
</tr>
<tr>
<td>Read noise</td>
<td>5 – 10 e⁻ (MIT),</td>
</tr>
<tr>
<td></td>
<td>20 e⁻ (SITe)</td>
</tr>
<tr>
<td>Dark current</td>
<td>&lt; 5e⁻ / hour @-100 deg</td>
</tr>
</tbody>
</table>
Field of View

Kiso Observatory, Institute of Astronomy, School of Science, the University of Tokyo

Kiso new wide-field camera
20 deg$^2$ in $\phi$ 9 deg, CMOS

Kiso Schmidt telescope
$\phi$ 9 deg

KWFC/Kiso
4.8 deg$^2$, CCD

ZTF (1.2m), 47 deg$^2$ (2016-)

iPTF (1.2m), 7.8 deg$^2$
Pan-STARRS (1.8m), 9 deg$^2$
LSST (8.4m), 9.6 deg$^2$ (2023-)
the Tomo-e Gozen Camera; Tomo-e

- Telescope: Kiso 105 cm Schmidt
- Field of view: 20 deg² in φ 9 deg
- Sensor: 1k x 2k CMOS sensor†
- Chips: 84
- Pixel scale: 1.2 arcsec/pix
- Frame rate: 2 frames/sec (max)
- Filter: SDSS-g+r, SDSS-g, SDSS-r ‡

† Driven at ordinary temperature and pressure
‡ Manually exchange between filters in the daytime
the Tomo-e Gozen Camera

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- Chips: 84
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Tomo-e Gozen (Lady Tomo-e, 巴御前) born in the Kiso region in the 12th century and known with beauty and bravery.
Detection Capability for Transient Events

GW optical counter parts
Flaring stars
GRBs
Satellite, Debris
Meteors
White dwarfs
Neutron stars
Occultation of TNOs

The numbers in the circles indicate limiting magnitudes.
Rare and Transient Phenomena

- Shock Breakout of core-collapse SN
- Explosion of Nova
- Optical follow up of Gravitational wave
- Afterglow of Gamma-ray burst
- Optical candidate of fast radio burst
- X-ray time variable objects
- Transit of Exoplanet
- Occultation by Trans-Neptune object
- Potentially Hazardous Asteroid
- Faint meteor
Outline

☐ Overview of Kiso wide-field CMOS camera, Tomo-e

☑ Development of Tomo-e

☐ New science capability with Tomo-e
Focal Plane

- Total sky coverage: 20 deg$^2$
- Total 190 Mpixels
- 760 MB/exposure

35mm Full HD CMOS sensor

- Package area = 0.3

φ 9 degree vignetting 0.44 mag
φ 4 degree vignetting free area

x 84 chips
**CMOS Imaging Sensor**

*35 mm full HD CMOS sensor* developed by Canon and U-Tokyo based on products for commercial use.

- Low dark current at Room temperature
- Low readout noise in Fast frame rate

### Specification

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixels</strong></td>
<td>2000 x 1128</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>19 μm</td>
</tr>
<tr>
<td><strong>Architecture</strong></td>
<td>Front side illuminated + micro lens array</td>
</tr>
<tr>
<td><strong>Surface protection</strong></td>
<td>Cover glass with AR coating</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>16 ch differential analog out</td>
</tr>
<tr>
<td><strong>Internal amplifier</strong></td>
<td>G = x1, x4, x16, x64, x256</td>
</tr>
<tr>
<td><strong>Frame rate</strong></td>
<td>30 fps (max)</td>
</tr>
<tr>
<td><strong>Read out mode</strong></td>
<td>Rolling read out</td>
</tr>
<tr>
<td><strong>Power dissipation</strong></td>
<td>1.8 W @30 fps</td>
</tr>
<tr>
<td><strong>QE (Aη)</strong></td>
<td>0.45 @λ_{peak}=500nm, 0.25 @λ=380, 700nm</td>
</tr>
<tr>
<td><strong>Read out noise</strong></td>
<td>2.3 e⁻ rms @30 fps @G = x16</td>
</tr>
<tr>
<td><strong>Dark current</strong></td>
<td>0.05 e⁻/pix/sec @273 K</td>
</tr>
<tr>
<td><strong>Saturation</strong></td>
<td>55,000 e⁻/pix @G = x1</td>
</tr>
<tr>
<td></td>
<td>5,700 e⁻/pix @G = x16</td>
</tr>
<tr>
<td><strong>Filling factor</strong></td>
<td>Sensor area/Package area = 0.3</td>
</tr>
<tr>
<td><strong>Package size</strong></td>
<td>60.9 mm x 44.6 mm</td>
</tr>
</tbody>
</table>
Evaluations of Front-side CMOS Sensor

Laboratory test and Test observations in U-Tokyo (2012-2013)

- Readout noise
- Cross talk, Hysteresis
- Linearity, Dynamic range, Flatness
- Photometric accuracy
- Quantum efficiency, Sensitivity
- Aperture ratio, Efficiency of micro lens
- Dark current
- Temperature dependence (20 – 60 degrees)

35mm Full HD CMOS sensor

CMOS sensor mounted on Kiso Schmidt telescope
First light observations 2012/12/16-17

FoV 40’ x 20’

High dynamic range image
M42 Orion star-forming region
1/30 sec x1,000 frame x 2 bands

Long integration time image
NGC891 nearby edge-on galaxy
2 sec x100 frame x 5 dithers, V band

Kiso Observatory, Institute of Astronomy, School of Science, the University of Tokyo
Limiting Magnitude of Tomo-e

Background photons: 13 e^-/s/pix
Readout noise: 2.5 e^{-}
Dark current at 273 K: 0.05 e^-/s/pix

w/ broad band on Kiso Schmidt in dark sky (20 mag/arcsec^2)

Limiting magnitude of Tomo-e

<table>
<thead>
<tr>
<th>Integration time (sec)</th>
<th>V_{mag}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/10</td>
<td>15.3</td>
</tr>
<tr>
<td>1</td>
<td>17.2</td>
</tr>
<tr>
<td>10</td>
<td>18.7</td>
</tr>
<tr>
<td>100</td>
<td>19.9</td>
</tr>
</tbody>
</table>

- Higher sensitivity than CCD in \( t_{\text{integ}} < 10 \) sec.
- Higher exposure efficiency expected in continues observations because of zero readout time.
Photometric Accuracy

- Photometric degradation originated from microlens array not confirmed.
- Photometric accuracy depends on a frame rate.

Measured photometric error

- PSF on microlens array
- 1.2 arcsec/pix
- Sufficient over-sampling

- Time variation of atmospheric refractive index
  \[ \rightarrow \text{Flux time-variation} \]
Cross talk and Hysteresis

- Cross talk in the same frame
  - Between separated pixels: $< 10^{-8}$
  - Between neighbor pixels: not measured

- Hysteresis between frames
  - A few second time scale: $< 10^{-6}$
  - Sub-second time scale: not measured

Good performance on cross talk and hysteresis confirmed
Conceptual Design of Camera System

- **Mosaic mount of CMOS sensors**

  On a spherical surface of $R = 3,300$ mm

- **Optical alignment accuracy**

  Alignment accuracy of ± 100 μm required

- **Thermal and structural design**

  Ordinal pressure and Room temperature inside the chassis

- **Video readout circuit**

  - Differential amplifiers and A/D convertors
  - Total power dissipation is 30 W.

- **FoV center**

<table>
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<tr>
<th>Defocus [μm]</th>
<th>6 arcsec (100μm)</th>
</tr>
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<tbody>
<tr>
<td>-100</td>
<td>-100</td>
</tr>
<tr>
<td>-50</td>
<td>-50</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>+50</td>
<td>+50</td>
</tr>
<tr>
<td>+100</td>
<td>+100</td>
</tr>
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</table>

- **λ = 420 nm**
Large amount of data (760 MB/sec, 27 TB/night) is produced in 2 fps observation. → Drastic reduction of raw data is required to record in storage.

**Base design of data handling system**

1. **Camera**
2. **Control PC with storage for 1 night**
3. **Primary server with storage for 10 nights**
4. **Secondary server with storage for 600 nights**

Transfer raw data in night time (27 TB/night)
Transfer raw data in day time (27 TB/day)
Transfer reduced data in the next night time (270 GB/day)

Reduce raw data to 1/100 size by cropping valuable image area and co-adding 100 frames.

Rapid reduction is required.
Tomo-e will be commissioning in 2017

<table>
<thead>
<tr>
<th>Year</th>
<th>Sensor development</th>
<th>Sensor evaluation</th>
<th>Data acquisition system</th>
<th>Chassis</th>
<th>Assemble</th>
<th>Test observation</th>
<th>Tomo-e/84chips camera</th>
</tr>
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<tbody>
<tr>
<td>2014/4</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2015/4</td>
<td></td>
<td>✫</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2016/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>✫</td>
<td></td>
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<tr>
<td>2017/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✫</td>
</tr>
<tr>
<td>2018/4</td>
<td></td>
<td></td>
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</table>

**↑ commissioning**
Outline

- Overview of Kiso wide-field CMOS camera, Tomo-e
- Development of Tomo-e
- New science capability with Tomo-e
Observation Strategy of Tomo-e

(1) 1-hour-cadence all-sky monitoring
   (high-cadence + very-wide-field)

(2) 20-fps wide-field monitoring
   (very-high-cadence + wide-field)

(3) Synergy with high-energy astronomy
   (very-wide-field + quick follow-up)

(4) Near and interior Earth objects
   (wide-field monitoring for fast moving objects)
**Observation plan**

- All sky (10,000 deg²), 1 hour cadence
- Recording period: 3 years
- Observation sequence:
  - 4 dithers x 170 pointing
  - short exposure (3 sec) → readout (0 sec) → dithering (2 sec)
- Limiting magnitude: $V_{\text{mag}} \sim 18$ (1 hour cadence)
  $V_{\text{mag}} \sim 19$ (1 day cadence)

**Expected results**

- Bright, but Rare and Fast time-variable events
- Supernovae, Neutron star mergers, AGNs, Gravity lensing
- Novae, Stellar flares, Eclipsing binaries, Late type star, Exosolar planets
- Bursts of comets and asteroids
- Unknown transient phenomena
High-cadence All-sky SNe survey

- Early phase light curve to constrain SN Ia progenitor
- Shock breakout of core-collapse supernovae

Tomo-e has 5 times higher capability than KWFC/Kiss SN survey (P.I. T. Morokuma) to detect SN shock breakouts.

Spectroscopic data of all objects discovered by this survey can be obtained by 1 – 2 m class telescopes.
### Expected detection rates of Novae and SNe

N. Tominaga+ 2014/10

#### 1 hour cadence, all-sky, 18 mag

<table>
<thead>
<tr>
<th>Event</th>
<th>Detection rate (events/year)</th>
<th>including M31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early phase of Nova</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Shock breakout of C-C SN</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

#### 1 day cadence, all-sky, 19 mag

<table>
<thead>
<tr>
<th>Event</th>
<th>Detection rate (events/year)</th>
<th>(M_v \sim )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discovery of Nova</td>
<td>10</td>
<td>-18 mag, 260 Mpc</td>
</tr>
<tr>
<td>Early phase of Ia SN</td>
<td>1,600</td>
<td>-18 mag, 260 Mpc</td>
</tr>
<tr>
<td>Early phase of C-C SN</td>
<td>300</td>
<td>-16 mag, 100 Mpc</td>
</tr>
<tr>
<td>Superluminous SN</td>
<td>30</td>
<td>-21 mag, 1,000 Mpc</td>
</tr>
<tr>
<td>SN in Near-by Galaxy</td>
<td>0.5</td>
<td>-11 mag, 10 Mpc</td>
</tr>
<tr>
<td>Discovery of Faint SN</td>
<td>unknown</td>
<td></td>
</tr>
</tbody>
</table>
Observation plan

• 2 deg$^2$ (partially readout) in φ 9 deg
• 20 frame/sec
• Continuous monitoring of 10,000 stars
• Recording period: 1 year
• Limiting magnitude: $V_{\text{mag}} \sim 14$

Expected results

**Very bright**, but **Rare** and **Very Fast time-variable** events

• Stellar occultations by Solar system objects
  - Duration time: a few 100 msec, Rate: a few dozen events/year
• Optical counterparts of Fast Radio Bursts
  - Duration time: ~10 msec, Rate: 0.5 events/day (when brightest case)
• X-ray variable objects: AGNs, YSOs, stellar flares

by Totani-san (private communication). Note, this flux estimation contains an inaccuracy of 7 orders.
Stellar occultations by TNOs

- TNOs (Trans Neptune Objects) keep composition in pre-solar age.
- Bodies with km-size are important.
- It is too small to detect them even with large telescopes.
  ➔ Stellar occultations
  ➔ Fast (20 fps) wide-field monitoring by Tomo-e
  A few events/year

Size and distance of TNOs

http://hubblesite.org/newscenter/archive/releases/2009/33/image/c/format/web_print/
Synergy with High-energy Astronomy

Gravitational wave detector
KAGRA
N-N merger?
N-B merger?
Core collapse SN?
Magnetar?

Neutrino detector
Super-Kamiokande
Nearby Supernova

Gamma-ray telescope
SWIFT, Fermi, MAXI
Gamma-ray burst

External trigger
w/ error of arrival direction: a few degrees

Optical wide-field follow-up by Tomo-e
Gravitational Wave Counterpart

- **Collapsar**, Long GRB
  NS/BH formation
  $< 10$ Mpc for GW

- **Magnetar Flare**, Short GRB
  NS oscillation
  $< 10$ kpc for GW

- **Neutron Star Merger**, Short GRB
  NS-NS/NS-BH
  $< 200$ Mpc for GW

- **Detachable distance** $< 250 – 300$ Mpc
  for GW from Neutron Star merger

- **Error circle of arrival direction of GW** $\sim \phi 5$ deg

- **Tomo-e** can follow-up GW events with $\phi 9$ deg

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**Kiso Observatory**, Institute of Astronomy, School of Science, the University of Tokyo

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**KAGRA**, JAPAN
**GEO600**, UK-GR
**LIGO**, x2, USA
**VIRGO**, IT

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**Collapsar**, Long GRB
**Magnetar Flare**, Short GRB
**Neutron Star Merger**, Short GRB

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**Detectable distance** $< 250 – 300$ Mpc
for GW from Neutron Star merger

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**Estimation of arrival direction of gravitational wave.**
Hayama (NAOJ) 2012
### Observation plan
- Phenomena in background
- During other surveys

### Expected results
- Faint meteor (sporadic and meteor shower)
  - Rate: a few dozen events/min
  - Brightness distribution of meteors.
  - Is the power law extended to faint meteors?

- Fast moving NEOs including PHA (Potentially Hazardous Asteroid)
  - Moving speed: 10-100 arcmin/sec
  - Such fast moving asteroids are not detected by CCDs with an ordinal FoV and exposure time.
Summary

Kiso Wide-field CMOS camera : Tomo-e

- Telescope: Kiso 105 cm Schmidt
- Field of view: 20 deg² in φ 9 deg
- Sensor: 84 CMOS chips
- Frame rate: 2 frames/sec (max)
- Commissioning: 2017
- Outstanding issue: Data handling and storage

Scientific strategies

- 1-hour-cadence all-sky monitoring
- 20-fps wide-field monitoring
- Synergy with high-energy astronomy
- Near and interior Earth objects

Rare and Transient Phenomena
Sub-second Time-domain