Instrument of the prime focus on the Subaru telescope

Masahiko Kimura
content

• What is Subaru telescope
• Why we use the prime focus?
  – merit vs. demerit
• Suprime-Cam
• FMOS (today’s main talk)
• HSC
• PFS (today’s sub-main talk)
• Summary/Conclusion
What is Subaru telescope

Primary Mirror
* Effective diameter: 8.2 m
* Thickness: 20 cm
* Active support: 261 actuators
* Weight: 22.8 tons
* Material: ULE (ultra-low thermal expansion glass)
* Mean Surface error: 12 nanometer
* Focal length: 15 m

Telescope Structure
* Mounting: altitude-azimuth (Alt-Az)
* Basic Optics: Ritchey-Chretian System
* Height: 22.2 m
* Maximum width: 27.2 m
* Weight: 555 tons
* Foci: Four
  - Primary focus: F2.0 (with corrector lens)
  - Cassegrain focus: F12.2
  - Nasmyth focus (optical): F12.6
  - Nasmyth focus (infrared): F13.6
Instruments

AO188
- Subaru 188-elements Adaptive Optics system
- diffraction-limited images in the near-infrared

COMICS
- Cooled Mid-Infrared Camera and Spectrograph
- imaging and spectroscopy from 8-25 microns

FMOS
- Fibre Multi Object Spectrograph
- Multi-object spectroscopy from 0.9-1.8 microns

FOCAS
- Faint Object Camera And Spectrograph
- optical imaging and longslit and multi-slit spectroscopy

HDS
- High Dispersion Spectrograph
- extremely high-resolution optical spectroscopy.

IRCS
- Infrared Camera and Spectrograph
- imaging from 0.9-5.5 microns
- low-resolution and echelle spectroscopy

MOIRCS
- Multi-Object Infrared Camera and Spectrograph
- imaging and low-resolution spectroscopy
- from 0.9-2.5 microns, 4* 7 arcmin field of view.

Suprime-Cam
- Subaru Prime Focus Camera
- optical imaging, 30 arcmin field of view
Prime focus

3 secondary mirror
3 prime focus units
## Merit vs. Demerit

using the prime focus.

<table>
<thead>
<tr>
<th>Merit</th>
<th>Demerit</th>
</tr>
</thead>
<tbody>
<tr>
<td>a small number of the focal ratio</td>
<td>a severe limit of the weight of the prime focus instrument</td>
</tr>
<tr>
<td>a wide field of view, suitable for the survey observations.</td>
<td>a laborious work</td>
</tr>
<tr>
<td></td>
<td>a risk of giving a serious damage to the main mirror by falling items from the instrument</td>
</tr>
</tbody>
</table>
a laborious work,
a risk of giving a serious damage to the main mirror
Serious Hardware Incident with the Subaru Telescope (Suprime-Cam) Interrupts Its Operation

While shutting down the observation system at the end of the night shift during the early morning of Saturday, 2nd, July 2011, the telescope operator detected an error signal from the top unit of the telescope.

@ Subaru Web page

We need to consider risks of giving a serious damage to the telescope and instruments.
But, invaluable advantage

a small number of the focal ratio

a wide field of view, suitable for the survey observations.
Suprime-Cam

- mosaic camera
  - ten - 2048 x 4096 CCDs
- 34' x 27' field of view
  - a pixel scale of 0.20''.
- Pixel size 15 um
- Gain 2.5-3.7 e-/ADU
- Read noise 10 e-
- Readout time 18 s

- hold 10 filters at a time
- Filter exchange time 300 s

Condition:
S/N=5, 1 hour exp. good (0.5'') seeing a moderately dark sky (3 days from New Moon)
FMOS

- **Fibre Multi-Object Spectrograph**
- 400 fibres on the prime focus
  - 30' diameter FoV
- Each fibre (100 μm core)
  - ~ 1".2 on the sky.
- Wavelength coverage
  - 0.9 – 1.8 μm
- 2 spectrographs (200 spectra x 2)
  - operated at T= - 50 deg.
  - OH– airglow suppression
- Two spectral resolution modes:
  - Low R: R~500 (one exposure)
  - High R: R ~ 2200 (any ~ 0.2 μm)
- FMOS consists of
  - Prime Focus unit
  - Echidna fibre positioner & fibre cables and connector
  - Two cooled spectrographs
FMOS instrument team

- Kyoto
  - Instrument PI (Toshinori Maihara)
  - Prime focus instrument bay
  - One OHS spectrograph
  - Observation software
- Oxford/RAL
  - Spectrograph Design
  - One OHS spectrograph
  - Fibre back-illumination system
- Durham
  - Fibre cables
  - Top end fibre connector
  - Slit assemblies
- AAO
  - ECHIDNA fibre positioner & software
  - Prime Focus Corrector
- Subaru
  - New floor to house spectrographs
• Mechanical/Optical structures of FMOS
  – Prime focus unit for IR
  – Fibre Positioner “Echidna” and Fibre connectors
  – Two cooled spectrographs

• Results

• Conclusion
Prime focus unit for IR

- Fibre positioner “Echidna”
- Wide-field corrector lens
- Instrument rotator with Cable wrapper

Optical adjustment mechanism
- Focus adjustment mechanism (FAM)
- Corrector movement mechanism (CMM)

Optical measurement systems
- Auto-guide system using fibre bundles
- Shack Hartmann system
Fiber positioner

• FMOS is mounted the prime focus of the telescope. And there is not enough space in the prime focus unit.
• So, we developed new type of fibre positioning.
  – Spine type fibre positioner!

The patrol area of each fibre is $\varphi 7\text{mm}$ diameter.

The spacing between neighboring spines is 7mm.
Fibre positioner “Echidna”

- Echidna
  - Using tube piezo actuator
- Focal plane imager
  - Two cameras:
    - Spine camera
    - Sky camera
Two Spectrographs

IRS1
@Kyoto Univ.

IRS2
@Oxford Univ. & RAL

Optically identical

Size
~ 2.5m x 3m x 2.5m
Two Spectrographs

- Schmidt Plate
- Folding Mirror
- Grating
- 1.4m Main Mirror
- Collimated
- Camera
- Fibre Slit (200 fibers)
- F/5
Two Spectrographs

[Diagram showing parts of the spectrographs]

Only used in Low R mode as “anti-disperser.” Removed in High R mode.
content

• Mechanical/Optical parts of FMOS

• Results
  – How to observe?
  – Previous commissioning/common use observations
  – Fibre Auto guiding
  – Echidna accuracy
  – Spectrum image
  – Performance

• Conclusion
Planning Observation

1. Prepare a source list of science targets
   1. Astrometry
   2. Guide star
   3. Coordinate calibration stars

2. Fibre allocation
   1. Field centre
   2. Position angle
   3. Observation method (sky background subtraction)
      1. Normal beam switching
      2. Cross beam switching

3. Spectrographs
   1. Low/high resolution mode
   2. Exposure time
   3. Calibration data
Observation Procedure

1. Pointing the telescope & allocating fibres (include focusing)
   1. Iterative process: Measure fibre positions and move spines.
      (back-illumination light + spine camera)
      Need 7 iteration (~15min.) > ~10um (0".12)
   2. Check field
      Filed check using coordinate calibration star, offset-pointing and
      rotation angle
2. Star auto guide ~20 min.
3. Start exposure
4. Re-configuration every 30 min. (~11min.)

On-source 3 hour exposure:

\[ 20\text{min} + (30 + 11)\text{min} \times 6 = 266\text{min} \]
\[ \text{overhead} = (266 - 180) \div 266 \times 100 = 32.3\% \]

4. Data acquisition for flat-fielding and wavelength calibration
Previous observations

- FMOS project started from 1999?
- Assembling started from 2005/May at Subaru telescope site
- Engineering first light @ 2008/May
- Scientific engineering observation start form 2009/Dec
- Scientific observation start from 2010/May/28.
- Open-use observation start from 2010/May/29.
A guide fibre bundle = 0”0.6 x 7 fibres
R =16-17 mag stars worked for AG

Fibre Auto Guide

400 science fibers
Populated within this 30’ diameter FoV (~15cm)

14 fibre bundles
For Auto-Guide
Fibre Auto Guide

Median AG2-error ~ 0".063
90% value ~ 0".139, 95% value ~ 0".173

Sky condition:
21/Apr/2010 night log
MASS ~ 0".24 ± 0".12
@CFHT WX Tower seeing
Echidna’s allocation error

Fibre allocation ⇒ using catalogs

On-sky fibre position ⇒ Telescope pointing

Telescope model ,,,

offset: 0".5 ~ 1".0

Measured offset between the target and fibre

5 x 5 tel. offset + exposure
⇒ 2D map of flux (spectrographs)
⇒ Centroid of star
Positing accuracy of Echidna

Fine-tune telescope model with “rastering” Configure spines based on the above telescope model, and acquire spectra of 400 fibers by “rastering” telescope.
Position offset between the targets and science fibres
~ 0”.15 in rms
Observation!

- **Data sets @from Dec 2009**
  - SXDF field: 120 min exp time
  - Lockman Hole: 90 min exp time
  - And 5 other fields

- **Data analysis:**
  - Estimate continuum flux by 5-ord Polynomial smoothing
  - Estimate emission line flux by Gaussian-fitting
  - Only use data in J-band ($\lambda=1.1-1.35$) & H-band ($\lambda=1.4-1.7$)
  - Estimate noise by using 1d-spectra
Detector image

Ramp sampling image at 15min exp. time

Object – Sky

Reduction
IRS1 vs. IRS2
Reduction image

- [OIII] 4959.5007
- Hα
Continuum flux sensitivity

A low resolution spectrum

- CBS mode
  - 1.5 hrs exp. Time
  - J = 20.1 mag., H = 19.7 mag
  - S/N = 4.9 @J-band, 4.5 @H-band

- CBS mode
  - 2hrs exp.time
  - J = 20.0 mag., H = 19.6 mag
  - S/N = 5.9 @J-band, 6.4 @H-band
Continuum flux sensitivity

Results:
J-band ~20.1 mag
H-band ~19.8 mag
@ 1hrs, S/N=5

Lockman Hole field
CBS mode
1.5 hrs epx. time
Emission line sensitivity

An emission line galaxy at z=1.5. [OIII]5007 emission is detected with S/N~24, of which flux is estimated to be \( \sim 5.4 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \).

An AGN at z=1.35. the narrow [OIII]5007 emission is detected with S/N~5, of which flux is estimated to be \( \sim 8 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \).
Emission line sensitivity

J-band: $1.0 \times 10^{-16}$ [erg/cm$^2$/s]
H-band: $0.9 \times 10^{-16}$ [erg/cm$^2$/s]
@1 hrs, S/N=5
Conclusion of FMOS

• Open-use observation begin in May 2010.
• Allocate fibres (include focusing)
  need 7 iteration (~15min.) within 10um(0”.12)
• Need re-configuration every 30 min.
  On-source 3 hour exposure:
  \[ 20\text{min} + (30 + 11)\text{min} \times 6 = 266\text{min} \]
  overhead = \( \frac{266 - 180}{266} \times 100 = 32.3\% \)
• Median AG2-error \( \sim 0”.063 \) @ MASS \( \sim 0”.24\pm0”.12 \)
• Continuum flux @ 1hr, S/N=5
  – J-band = 20.1 mag & H-band = 19.8 mag
• Emission line sensitivity @1 hrs, S/N=5
  – J-band = \( 1.0 \times 10^{-16} \) [erg/cm²/s]
  H-band = \( 0.9 \times 10^{-16} \) [erg/cm²/s]
SuMIRe Project
--- HSC and PFS ---
## History of HSC project

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone, Progress</th>
<th>Budget, Organization</th>
<th>People</th>
<th>Org.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Conceptual study of new lens</td>
<td>Subaru R&amp;D (Miyazaki+)</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2003~</td>
<td>CCD development, Mechanics concept study</td>
<td>Grants-in-Aid(Miyazaki+)</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>2005</td>
<td>ASIAA participation</td>
<td></td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>2006~</td>
<td>CCD production, Lens, Mechanics detail design</td>
<td>Grants-in-Aid (Karoji+)</td>
<td>33</td>
<td>4</td>
</tr>
<tr>
<td>2007</td>
<td>Princeton participation</td>
<td></td>
<td>~40</td>
<td>5</td>
</tr>
<tr>
<td>2008</td>
<td>NAOJ Subaru HSC project established</td>
<td></td>
<td>~40</td>
<td>5</td>
</tr>
<tr>
<td>2009</td>
<td>Design Review</td>
<td></td>
<td>~40</td>
<td>5</td>
</tr>
<tr>
<td>2010~</td>
<td>Stimulus Package (Murayama+)</td>
<td></td>
<td>~40</td>
<td>5</td>
</tr>
<tr>
<td>2012</td>
<td>Lens and PFU completed Camera completed (?)</td>
<td></td>
<td>~40</td>
<td>5</td>
</tr>
<tr>
<td>2012 ?</td>
<td>First Light (planned)</td>
<td></td>
<td>~40</td>
<td>5</td>
</tr>
</tbody>
</table>
### HSC

<table>
<thead>
<tr>
<th></th>
<th>Suprime-Cam</th>
<th>HSC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CCD Make and model</strong></td>
<td>Hamamatsu S10892-01</td>
<td>Hamamatsu S10892-02</td>
</tr>
<tr>
<td><strong>Number of CCDs</strong></td>
<td>10</td>
<td>104 + AutoGuide4 + AutoFocus 8</td>
</tr>
<tr>
<td><strong>Pixel</strong></td>
<td>15 micron square (0.2 arc-sec)</td>
<td>15 micron square (0.17 arc-sec)</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>34 arcmin x 27 arcmin</td>
<td>90 arcmin diameter</td>
</tr>
<tr>
<td><strong>Readout time</strong></td>
<td>18 sec</td>
<td>20 sec</td>
</tr>
<tr>
<td><strong>Number of filters</strong></td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td><strong>Filter exchange time</strong></td>
<td>300 sec</td>
<td>600 sec (900 sec while commissioning)</td>
</tr>
</tbody>
</table>
HSC

Φ82 cm
### PFS

<table>
<thead>
<tr>
<th>Field of View</th>
<th>1.3 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fibres</td>
<td>2400</td>
</tr>
<tr>
<td>fibre</td>
<td>$\Phi 128 \mu$m(core diameter) → 1.13 arcsec on the sky</td>
</tr>
<tr>
<td>Spectrograph</td>
<td>3-arm design, 4 sets 0.38-1.3$\mu$m</td>
</tr>
</tbody>
</table>
4-sets of Spectrograph

<table>
<thead>
<tr>
<th>3-arm</th>
<th>Coverage [Å],</th>
<th>Resolution [λ/Δλ]</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>3800-6700</td>
<td>2200</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>6500-10000</td>
<td>3500</td>
<td></td>
</tr>
<tr>
<td>IR</td>
<td>9700-13000</td>
<td>4500</td>
<td></td>
</tr>
</tbody>
</table>
Prime focus instrument for PFS
Fibre Positioning system

2400 Cobra Fibre positioners

Fibre arm

6 Auto guide cameras

http://www.newscaletech.com/app_notes/Cobra-JPL-article.html
### Fibre positioner

<table>
<thead>
<tr>
<th>Instrument</th>
<th>FMOS</th>
<th>PFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickname</td>
<td>Echidna (针鼹)</td>
<td>COBRA (眼镜蛇)</td>
</tr>
<tr>
<td>Type</td>
<td>Tubular piezo actuator</td>
<td>2-axis picomotor</td>
</tr>
<tr>
<td>Driving method</td>
<td>Tilt</td>
<td>Rotation</td>
</tr>
<tr>
<td>control</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Twisted fibre</td>
<td>○</td>
<td>×</td>
</tr>
<tr>
<td>Defocus</td>
<td>×</td>
<td>○</td>
</tr>
</tbody>
</table>
Measurement of the position and Auto guide

Not enough space
Metrology Camera System

in-plane position of each fibre tip within an error of 5 μm
the centroid of all imaged fibre tips in less than 3s
## Auto guide

<table>
<thead>
<tr>
<th>Instrument</th>
<th>FMOS</th>
<th>PFS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Fibre bundle</td>
<td>Direct image (CCD camera)</td>
</tr>
<tr>
<td><strong>merit</strong></td>
<td>Small space</td>
<td>Direct image, known seeing condition, focal plane distortion</td>
</tr>
</tbody>
</table>
What to do in ASIAA?

- Configuration, preliminary design and preliminary analysis will be by JPL
- Detailed design, analysis, fabrication, **handling fixtures** and test will by ASIAA
  
  almost ALL!
Conclusion

• We start a **realistic** design for the prime focus instrument.
Question and answer

Question:
How do you suppress OH airglow lines?

Answer:
We use a mask mirror. The mask is made of a thin (0.2mm in thickness) stainless-steel plate at the positions of the strong OH-airglow lines, and blackened to absorb the OH light.

More detail:

• [http://subarutelescope.org/Introduction/instrument/OHS.html](http://subarutelescope.org/Introduction/instrument/OHS.html)
Question and answer

Question:
Number density?

Answer:
The targets are randomly scattered over the field. FMOS use 400 spine type fibres with 7mm pitch. So, the number density of spines is 0.57 / arcmin^2., which is suitable for objects like Extremely-Red Objects, Submm-bright sources, Lyman Break Galaxies, and so on.