12. Instrumentation - Some topics

12.1 High resolution spectrographs - iSHELL and WINERED

Remember the tradeoff equation for the resolving power R:

$$R = \frac{D_{col}}{x_r} \frac{2\ tan\phi}{D_{tel}}$$

We discussed the trade off for a fixed grating (constant ϕ). If we have minimized x_r and maximized D_{col} (the slit width and collimator diameter respectively) and we still need more resolving power, we can increase the blaze angle ϕ. Spectrographs working in first order typically have blaze angles between 5 and 20°. High blaze angle gratings are called echelle gratings. A popular choice is 63.5°, for which $tan\phi = 2$. This is called an R2 grating.

Notes:
I compare iSHELL and WINERED as examples of a facility instrument and a PI-type instrument. The drivers for the design are very different and one can see how this affects the complexity of the instrument. One can also see the tradeoff of collimated beam diameter, slit size, and grating blaze angle to achieve the scientific and design goals.

Another version of the tradeoff equation is (see slide 9-14):

$$R = \frac{206265\, D_{col}}{x} \frac{m\lambda}{D_{tel}\,(d\, cos\beta)}$$

For a fixed D_{col} and x, the resolving power can be increased by using an echelle grating and working at a high order m.

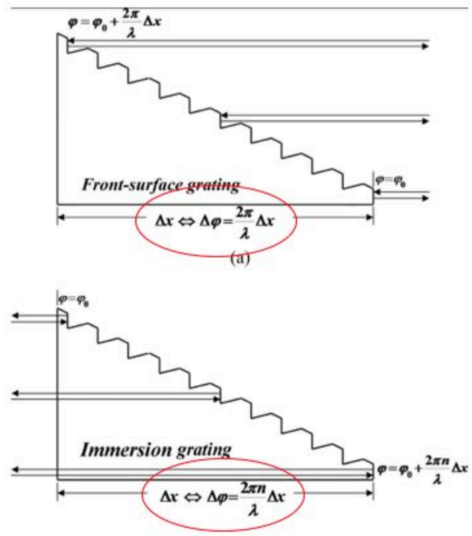
I briefly describe two instruments, iSHELL which uses an R3 immersion echelle grating (ϕ = 71.3°), and WINERED which uses an R5 echelle grating (ϕ = 79.3°).

Notes:

I gave a colloquium describing a new high resolution spectrograph for the NASA IRTF called iSHELL. This spectrograph uses an R3 immersion grating. I will only describe a few relevant things here.

Comparison of a front-surface grating and an immersion grating.

The path length difference is increased in an immersion grating by the index of refraction. This allows a higher spectral resolution to be obtained that is 3.4 times larger in the case of silicon.



Notes:

For an immersion grating spectrograph the resolving power is given by

$$R = \frac{\lambda}{\Delta\lambda} = \frac{2D_{col}}{xD_{tel}}\ n\ tan\phi$$

where n is the index of refraction.

Basic specifications of iSHELL:

- Slit widths: 0.375", 0.75", 0.8", 1.5" and 4.0"
- Resolving power of 75,000 at 1.2-5.3 μm

- Slit viewer: 42" diameter FOV at 0.12" per pixel

- Spectrograph array: 2K x 2K HgCdTe array with 5.3 μm cutoff
- Slit viewer array: 512 x 512 InSb array

- Silicon immersion grating produced by the Univ. Texas.

Notes:

Very few places can produce an immersion grating and they are made by two methods. One is by a photolithographic process whereby a mask is put on the silicon grating surface and the material is etched away. This process is very difficult to control but a group at the Univ. of Texas have succeeded (Marsh et al. 2007; Gully-Santiago et al. 2012).

Another method is to cut grooves into a material using a ultra-high precision 5-axis diamond cutting machine (Sukegawa et al. 2012;). This group is currently fabricating immersion gratings made out of CdZnTe, Ge, and InP. The basic properties are:

material	InP	Ge	CdZnTe
index of refraction	3.2	4	2.7
wavelength range	1.4-8.0 μm	2-11 μm	5-20 μm

This shows that the 1.4 -20 μm spectral region can be covered with immersion gratings. Also it shows that the cutting technique can utilize more materials than the etching techniques.

Notes:

Marsh, J. P., D. J. Mar and D. T. Jaffe (2007). "Production and evaluation of silicon immersion gratings for infrared astronomy." Applied Optics **46**: 3400-3416.

Gully-Santiago, M. et al. (2012). Near-infrared metrology of high-performance silicon immersion gratings. Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II. **8450**.

Sukegawa, T., S. Sugiyama, T. Kitamura, Y. Okura and M. Koyama (2012). High-performance astronomical gratings by Canon. Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II, SPIE. **8450**.

Sukegawa, T. and Y. Okura (2017). Three types of immersion grating for next-generation infrared spectrometer. SPIE. **10100.**

These figures show the quality of the gratings produced by Canon (Sukegawa and Okura 2017). Note the high quality of the grooves and the very clean line profile (no ghost lines).

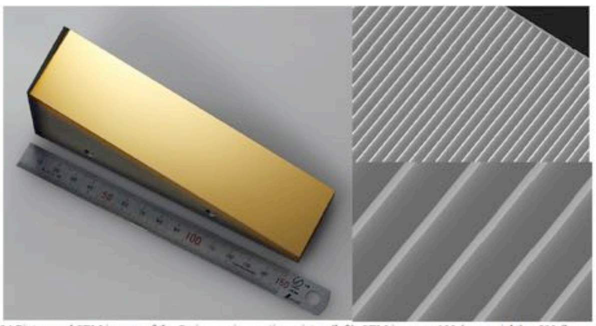


Fig.24 Picture and SEM images of the Ge immersion grating; picture(left), SEM images ×100 (upper right), ×500 (lower right)

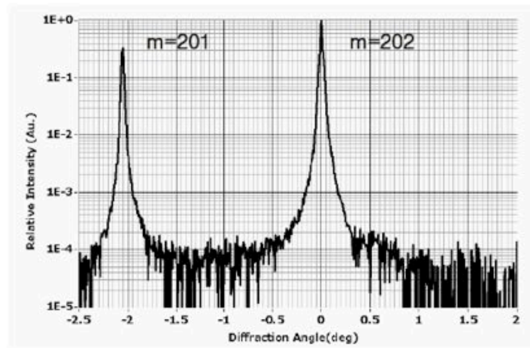


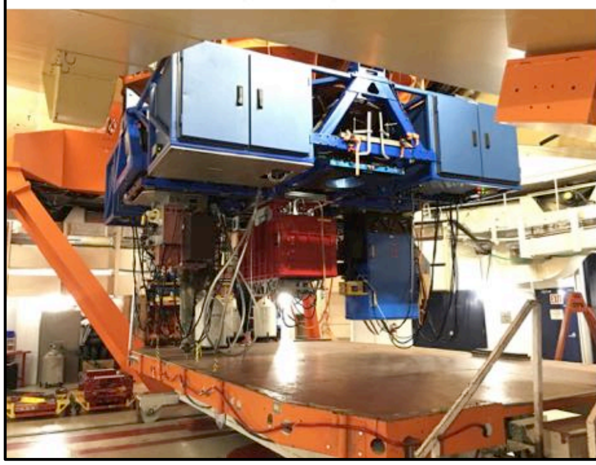
Fig.20 The measured diffraction lights (m=201,202) by green laser under the littrow condition in the air

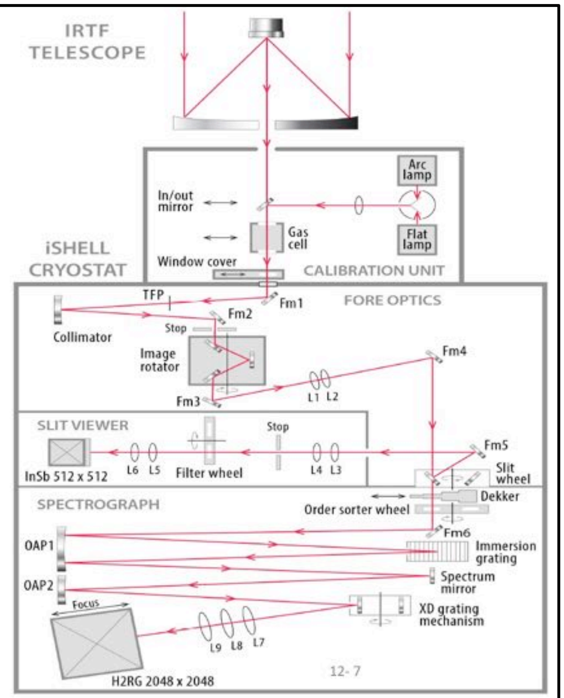
Notes:

Sukegawa, T. and Y. Okura (2017). Three types of immersion grating for next-generation infrared spectrometer. SPIE. **10100.**

iSHELL spectrograph layout. The instrument is designed to be a facility instrument so it has many observing modes and is complex. The optical throughput is about 0.16 (including detector quantum efficiency).

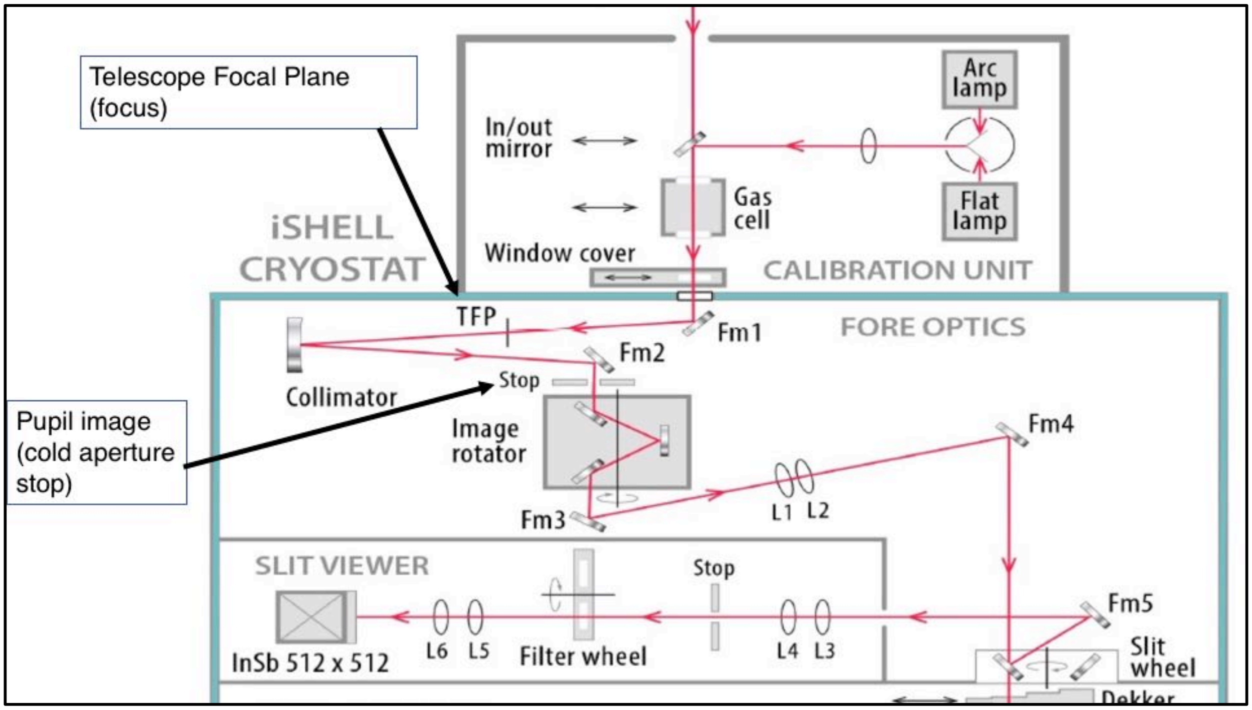
Photo of iSHELL (red box) on the IRTF:





Notes:

Rayner, J. et al. (2016). iSHELL: a construction, assembly and testing. Ground-based and Airborne Instrumentation for Astronomy VI. **9908:** 990884.



Telescope Focal Plane
(focus)
Pupil image
(cold aperture
stop)
iSHELL
CRYOSTAT
In/out
mirror
Gas
cell
Window cover
Arc
lamp
Flat
lamp
CALIBRATION UNIT
TFP
Fm1
FORE OPTICS
Collimator
Fm2
Stop
Image
rotator
Fm3
L1
L2
Fm4
SLIT VIEWER
Stop
Fm5
InSb 512 x 512
L6
L5
Filter wheel
L4
L3
Slit
wheel
Dekker

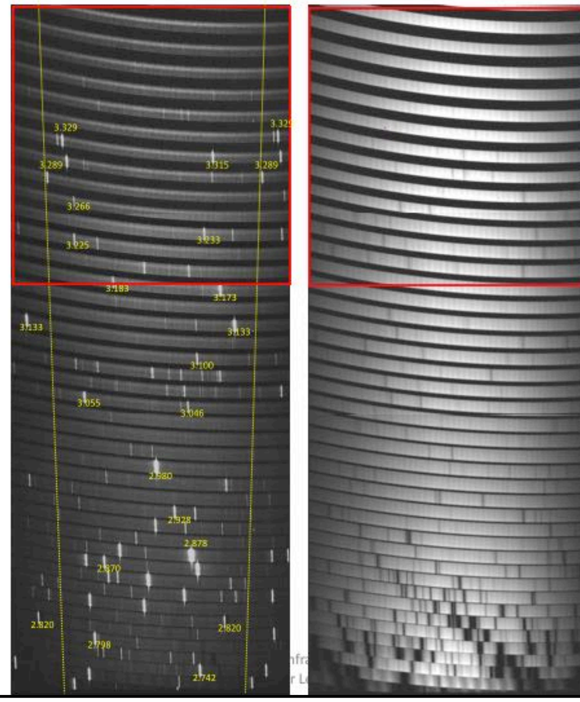
Notes:

iSHELL lab data of the L-band (2.8-4.0 μm).

The coverage with one exposure is shown by the red box. A thorium-argon arc lamp is shown on the left and a continuum source spectrum on the right. In the continuum source spectrum the absorption by water vapor in the room can be seen. The resolving power is 70,000.

iSHELL was optimized for working at L-band.

_L_-band
XD Mode
0.375" x15" slit



Notes:

WINERED

This is a high resolution spectrograph developed by the Laboratory of Infrared High Resolution Spectroscopy at Kyoto Sangyo University (Otsubo et al. 2016, Ikeda et al. 2016). It is a PI-type instrument used at the Koyama Astronomical Observatory and is now used at the NTT in Chile. N. Kobayashi is the PI.

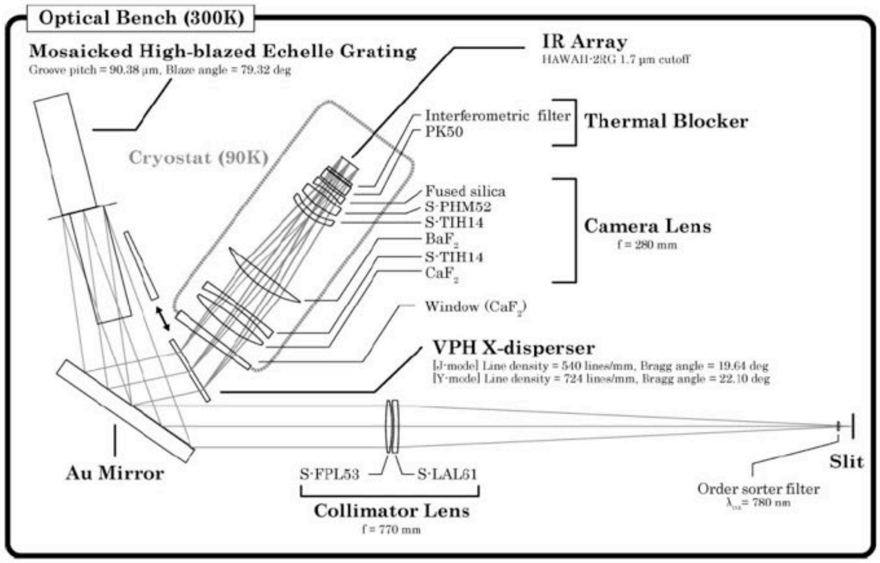
I want to mention this instrument to compare the design choices with the iSHELL spectrograph. The instrument specifications are:

Wavelength range: 0.9-1.35 μm
Spectral resolving power: WIDE mode is 28,000; Hi-res mode is 68,000 (designed for 80,000)
Slit widths: 100, 200, 400 μm
Echelle grating with blaze angle of 79.3^o (R5.3)
Array: 2Kx2K HgCdTe with 1.7 μm cutoff
Throughput: >50% in WIDE mode, >39% in Hi-res J mode
Room temperature optics

Notes:

Otsubo, S. et al. (2016). First high-efficiency and high-resolution (R=80,000) NIR spectroscopy with high-blazed Echelle grating: WINERED HIRES modes. Ground-based and Airborne Instrumentation for Astronomy VI, SPIE, **9908**.
Ikeda, Y. et al. (2016). High sensitivity, wide coverage, and high-resolution NIR non-cryogenic spectrograph, WINERED. Ground-based and Airborne Instrumentation for Astronomy VI, SPIE, **9908**.

WINERED Hi-res mode with a mosaic echelle grating. Cross-disperser is a Volume Phase Holographic (VPH) grating. Throughput of the instrument is maximized. Designed for room temperature to reduce cost and provide easy maintenance.



Notes:

Ikeda, Y. et al. (2016). High sensitivity, wide coverage, and high-resolution NIR non-cryogenic spectrograph, WINERED. Ground-based and Airborne Instrumentation for Astronomy VI, SPIE, **9908**.

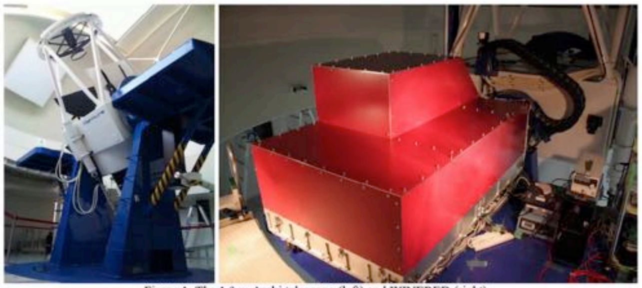


Figure 1. The 1.3 m Araki telescope (left) and WINERED (right).

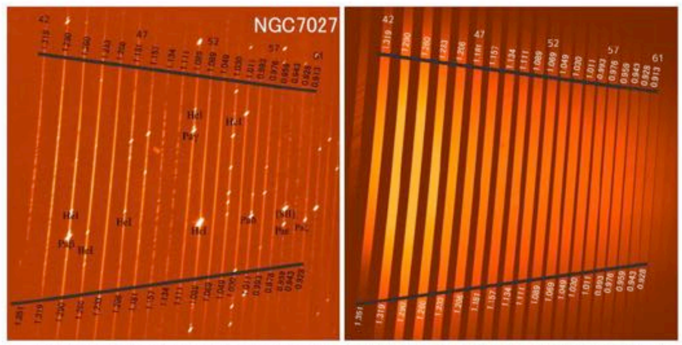


Figure 3. Echellograms in the Wide mode: NGC7027 (left) and a flat-lamp (right). The area between the two black lines show the free spectral range, and numbers indicate the shortest and longest wavelengths in μm for each order.

Notes:
Ikeda, Y. et al. (2016). High sensitivity, wide coverage, and high-resolution NIR non-cryogenic spectrograph, WINERED. Ground-based and Airborne Instrumentation for Astronomy VI, SPIE, **9908**.

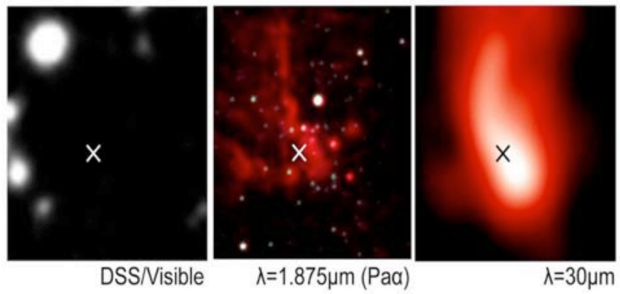
As a PI-type instrument WINERED is designed to be low cost, easy to maintain, high throughput for greater sensitivity, usable at different telescopes, and able achieve unique science.

This in contrast to iSHELL which is a facility instrument with many modes and is cryogenic to work at thermal wavelengths. It was necessary to sacrifice some throughput and accept higher complexity in order have great observing flexibility and coverage to 5 μm.

Notes:

12.2 Tokyo Atacama Observatory and instruments

This is an ambitious project to build a 6.5-m telescope at the summit of Cerro Chajnantor. At 5,640 m it is the highest site for a permanent observatory. The goal is to exploit the very low water vapor and the good weather conditions. A 1-m telescope (mini-TAO) is at the site to measure the site conditions and undertake scientific observations.



Mini-TAO (left) and observations of the Galactic Center in the Paschen α line and at 30 μm. This demonstrates the viability of observing at wavelengths that are totally obscured by water vapor elsewhere.

Notes:
http://spie.org/newsroom/6796-new-65m-ir-optimized-high-altitude-observatory-in-northern-chile

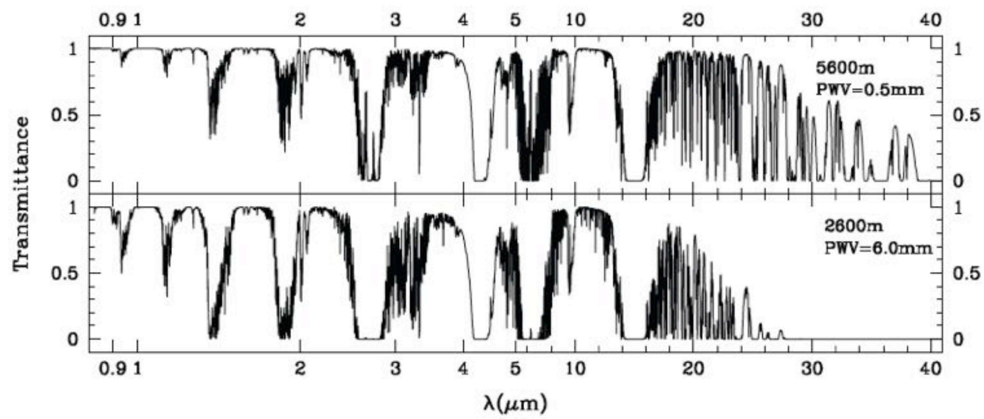


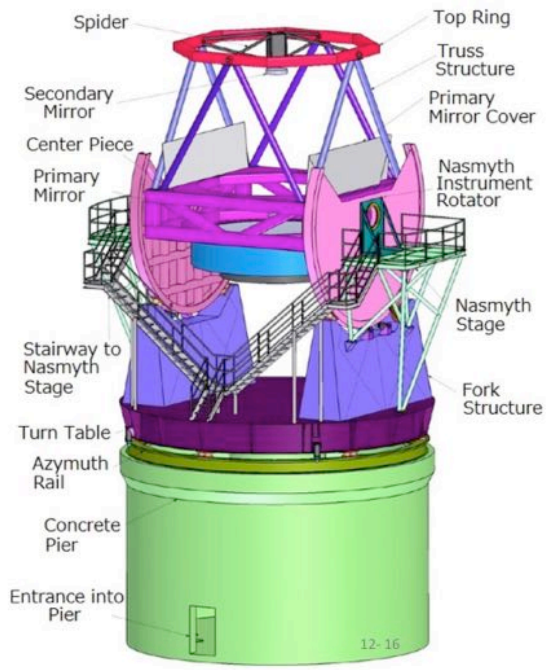
Fig. 1. Atmospheric transmittance curves in the near- to mid-infrared wavelength at the summit of Cerro Chajnantor (top) and at a typical observatory in Chile (bottom).

Notes:

Motohara, K. M. et al. (2011). Site Characteristics of the Summit of Cerro Chajnantor at the 5640 m Altitude. Revista Mexicana de Astronomia y Astrofisica Conference Series. **41:** 83-86.

6.5-m telescope specs (Yoshii et al. 2016)

- Design of the telescope is similar to the Magellan telescopes
- Secondary is 0.9-m in diameter. It is undersized to minimize thermal emission from the telescope Only the inner 6.15 m of the mirror is used.
- Focal ratio is 12.2 (like Subaru)
- 25 arc minute field of view
- 2 Nasmyth foci
- Remotely operated from San Pedro, about 50 km away



Notes:
Yoshii, Y. et al. (2016). The University of Tokyo Atacama Observatory 6.5m telescope: project overview and current status. Ground-based and Airborne Telescopes VI, SPIE. **9906**.

Fabrication of the telescope structure is finished shipment to Chile in progress.

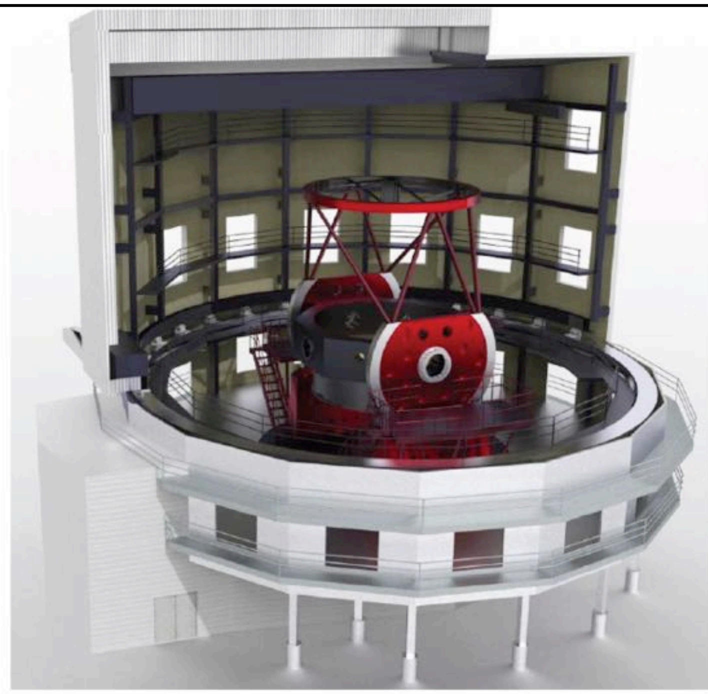
Notes:

TAO enclosure.

TAO has two main instruments: SWIMS and MIMIZUKU.

SWIMS - Simultaneous-color Wide-field Infrared Multi-object Spectrograph.

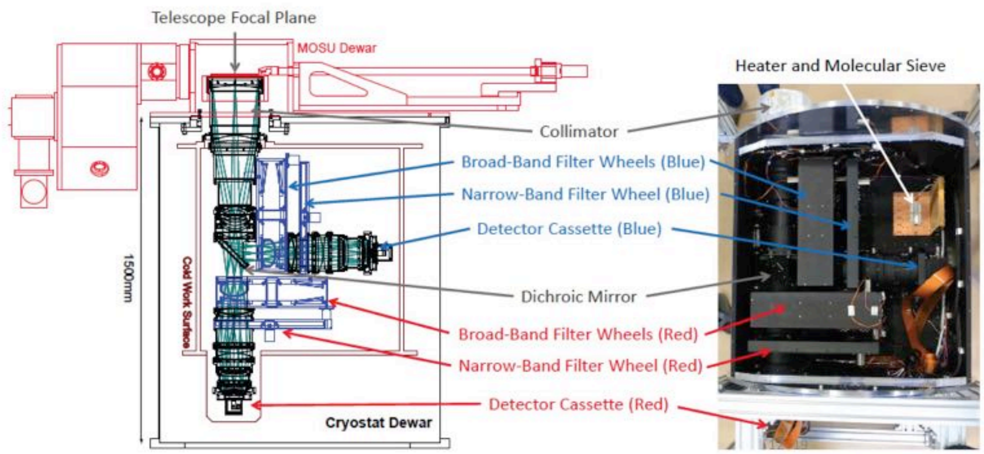
MIMIZUKU - Mid-Infrared Multi-field Imager for gaZing at the UnKnown Universe



Notes:

SWIMS (Motohara et al. 2016)

- 2 cameras, one for 0.9-1.4 μm and 1.45-2.5 μm, for simultaneous imaging and multi-object spectroscopy (MOS) at R=1000.
- 8.6x4.3 arcmin field of view with two 2Kx2K HgCdTe arrays
- Slit masks used for MOS. Has automatic slit changing mechanism called MOSU.
- Also plan to have IFU unit with 17"x13" field of view.



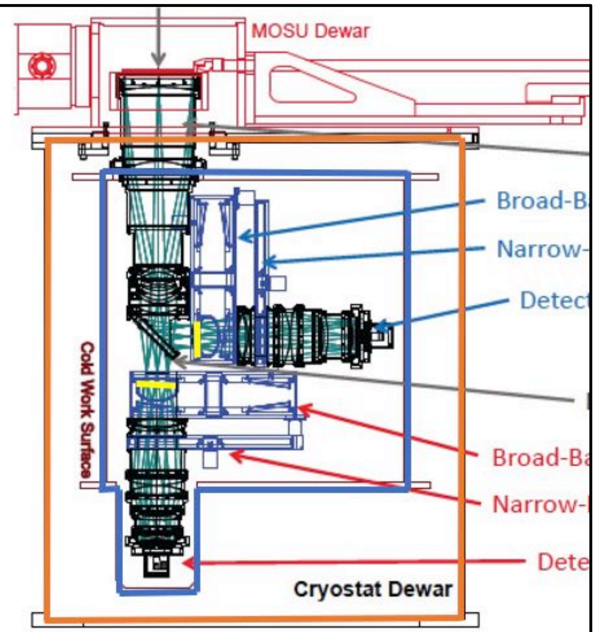
Notes:

Motohara, K. et al. (2016). NIR camera and spectrograph SWIMS for TAO 6.5m telescope: overview and development status. <u>Ground-based and Airborne Instrumentation for Astronomy VI, SPIE</u>. **9908**.

Note design items to reduce the background:

Cold radiation shield around the instrument.
Cold stop to block stray light.

Orange: vacuum jacket of the cryostat
Blue: cold work surface and cold radiation shield
Yellow: position of the cold stop.



Notes:

MIMIZUKU (Kamizuka et al. 2016)

Three cameras to cover 2.0-38 μm (see table below)
Imaging of two fields simultaneously to allow sky subtraction.

Table 1. Latest specifications of MIMIZUKU on the TAO 6.5-m telescope.

Channel	NIR	MIR-S	MIR-L
Wavelength	2.0–5.3 μm	6.8–26 μm	24–38 μm
Detector	Teledyne HAWAII-1RG HgCdTe (5.3 μm cutoff) 1024×1024 pix	Raytheon Aquarius Si:As IBC 1024×1024 pix	DRS MF-128 Si:Sb BIB 128×128 pix
Pixel scale	$0''.069$/pix	$0''.11$/pix	$0''.24$/pix
Field of view	$1'.2\times1'.2$	$2'.0\times2'.0$	$31''\times31''$
Imaging filters [a]	3 (+2)[b] medium bands, 1 narrow band	8 medium bands	2 medium bands
Spectroscopic modes [c]	*KL*-band, 2.7-μm band, *LM*-band	*N*-band, *Q*-band	30-μm band [d]

Notes:
Kamizuka, T. et al. (2016). Development status of the mid-infrared two-field camera and spectrograph MIMIZUKU for the TAO 6.5-m Telescope. Ground-based and Airborne Instrumentation for Astronomy VI, SPIE. **9908**.

MIMIZUKU will provide low-resolution spectroscopy from 2-28 μm.

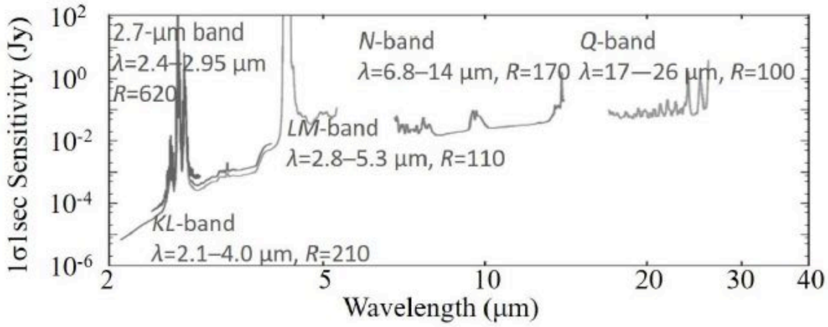


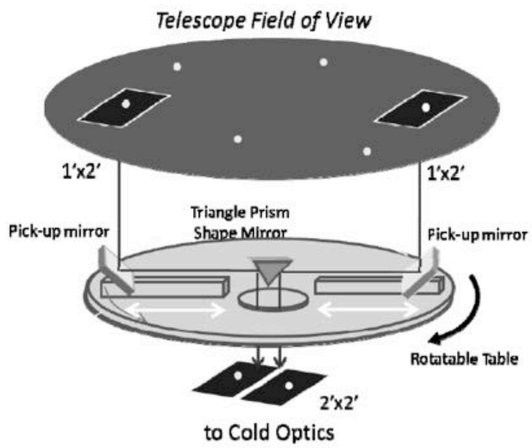
Figure 2. Expected continuum sensitivity for point-source spectroscopy.

Notes:

Kamizuka, T. et al. (2016). Development status of the mid-infrared two-field camera and spectrograph MIMIZUKU for the TAO 6.5-m Telescope. Ground-based and Airborne Instrumentation for Astronomy VI, SPIE. **9908**.

MIMIZUKU field stacker. It provides two images of the sky simultaneously on the same array. This will allow the sky to be subtracted. The sky field can be adjusted in distance from the object and in rotation angle. (Miyata et al. 2010)

To compensate for the change in telescope focus, the entire instrument can be moved up and down.



Notes:

Miyata, T. et al. (2010). Development of a new mid-infrared instrument for the TAO 6.5-m Telescope. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. **7735:** 124.