Lecture 11: Optical Telescopes and Instruments

Southern African Large Telescope (SALT) with a crescent moon

Rutgers Physics 346: Observational Astrophysics   April 6, 2021

Homework for Thursday, April 8

Due: Quiz #10 will appear on Canvas Assignments at 4:20pm, due at noon tomorrow.

Do: Be ready for a "Data Check" on your 2nd group project during Thursday's Project Meeting. Jack is advising Projects 7,8,11; Eric is advising Projects 9,10,12.

Quiz #9: Explain the two key pieces of evidence that implied that gamma-ray bursts occur outside the Milky Way, rather than inside the Milky Way or in our own solar system.

Answer: GRBs are isotropic, meaning they cannot come from the disk of the Milky Way, and many have X-ray counterparts that can be localized as extragalactic. Nowadays, it is common to take optical spectra of GRB afterglows to measure the redshifts of their host galaxies directly!

Responses to Mid-Course Evaluations

- Thanks to all 23 of you (out of 26 active students) who filled them out!
- Any of that feedback would have been welcome without anonymity – please communicate with us!
- We'll update Workshop instructions to be clearer and add video tutorials for future classes
- Let us know what's unclear about Project instructions; **some** ambiguity is intentional there so that you get the learning experience and enjoyment of figuring things out as a group
- Grades for 1st project Presentations and Reports were primarily group grades; will use Zoom poll to vote on approach for 2nd projects
- Project groups are encouraged to meet in Breakout Rooms on Tuesdays 4:30-5:00 starting today
- I'll add polls and videos to remaining lectures
- Lecture notes/textbook: "I forgot there was a textbook"
- Zoom poll to determine when 2nd project report will be due

Telescope access

In the U.S., there is a strong distinction between "public" and "private" OIR (optical/infrared) ground-based telescopes.

Public telescopes are operated by NSF's National Optical-Infrared Astronomy Research Laboratory ("NOIRLab"), at the...

+ Kitt Peak National Observatory (KPNO), in Arizona
+ Cerro Tololo Inter-American Observatory (CTIO), in Chile
+ international Gemini Observatory, in Hawaii & Chile
+ Vera C. Rubin Observatory, in Chile (coming soon!)

Anyone at a U.S. institution can propose for time on one of these telescopes (except for Rubin Obs.). (Specific international partners also have access to Gemini; Chilean astronomers have access to all telescopes in Chile.)

Telescope access

In the U.S., there is a strong distinction between "public" and "private" OIR (optical/infrared) ground-based telescopes.

Private telescopes are operated by specific institutions or institutional partnerships, and only astronomers at those institutions (or those with "hosting" privileges, a la Chile or Hawaii) are eligible to propose for time on them.

+ Keck Observatory, in Hawaii
+ Las Campanas Observatory, in Chile
+ Lick Observatory, in California
+ Palomar Observatory, in California
+ Large Binocular Telescope (LBT), in Arizona
+ Hobby-Eberly Telescope (HET), in Texas
+ Southern African Large Telescope (SALT), in South Africa (Rutgers has a ~10% share)

Telescope access

In the U.S., there is a strong distinction between "public" and "private" OIR (optical/infrared) ground-based telescopes.

A few comments about the public vs. private distinction…

(1) Two new "extremely large telescope" (ELT) projects (GMT and TMT) are seeking public (NSF) funding to supplement their private partners' funding, which would lead to a hybrid public/private status.
(2) NSF funding for instruments has previously been used to unlock some amount of open observing time.
(3) U.S. radio astronomy has historically used a very different "open skies" model, in which any astronomer anywhere in the world can propose to use a telescope operated by a U.S. observatory (NRAO, GBO, Arecibo).

Key properties of an OIR telescope

What is the diameter of its primary mirror(s)?

How is the surface of its primary mirror formed and maintained (e.g., segmented vs. spin-cast monolithic)?

How good is its site, in terms of seeing, transparency, and light pollution?

How capable are its instruments?

[related to next week's discussion] Is it equipped with adaptive optics?

Telescope diameter

A telescope's diameter is its most critical parameter, for (maybe) two reasons:

(1) collecting area $\propto D^2$, so bigger telescopes can observe fainter objects faster – especially important for spectroscopy, since light is being dispersed

(2) diffraction-limited resolution $\propto \lambda/D$, so bigger telescopes can (in principle) achieve higher angular resolution – helpful for both imaging and spectroscopy

In practice, unless a ground-based telescope is equipped with adaptive optics, resolution is seeing-limited rather than diffraction-limited.

Ground vs. space

Hubble Space Telescope is not limited by seeing, so it delivers diffraction-limited imaging without adaptive optics… but since it has only a 2.4m diameter mirror, a ground-based telescope with an 8–10m mirror can observe much fainter targets and (with adaptive optics) at higher angular resolution.

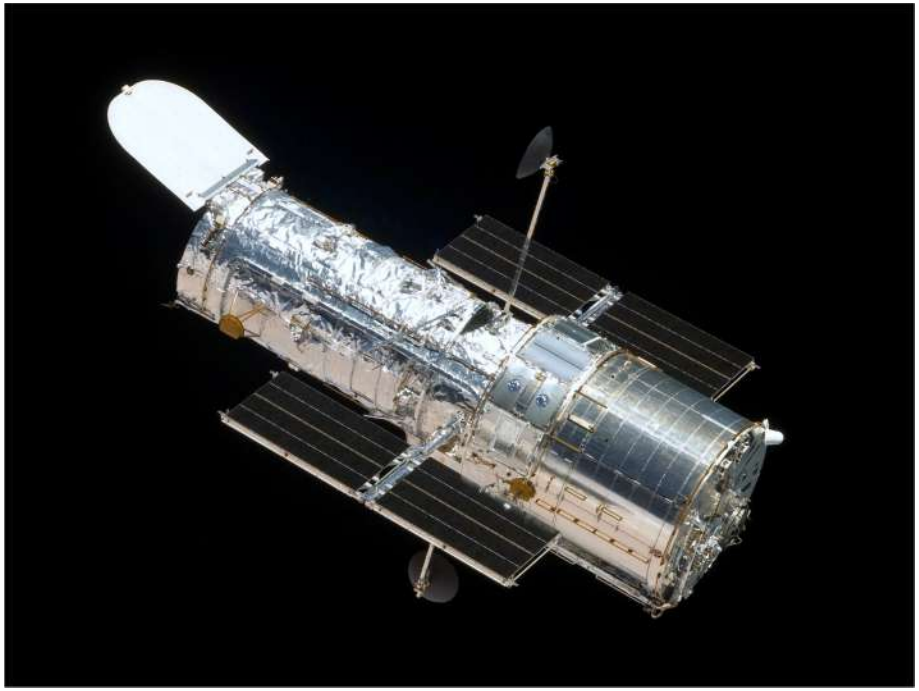
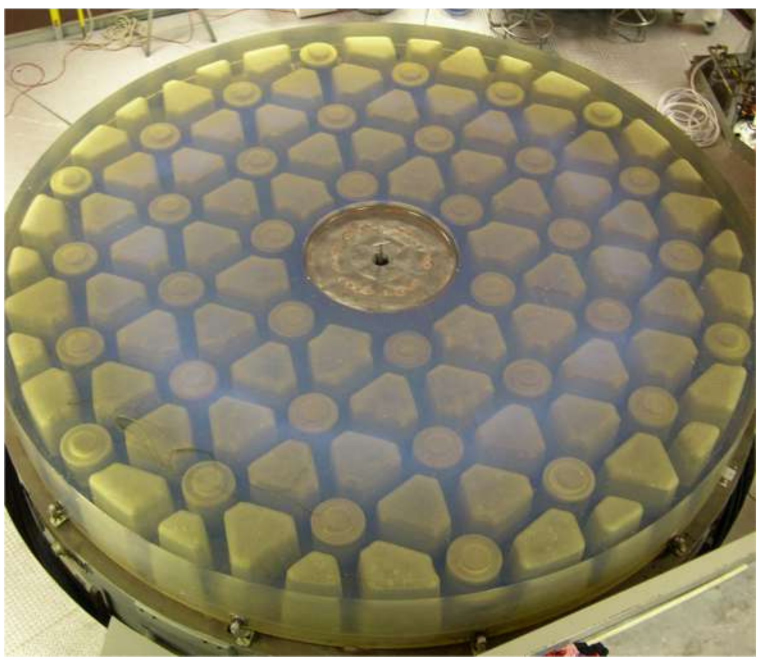


image credit: NASA

Typical space vs. ground division of labor:
imaging from space + spectroscopy from the ground.

How can we make a big mirror?

From 1949–1975, the largest telescope in the world was the 5.1m Hale Telescope at the Palomar Observatory. (After 1975, it still outperformed the 6m BTA-6 telescope in Russia, but in 1990 was finally surpassed by the first Keck Telescope.)



Mirror was cast by Corning as a single Pyrex blank (low coefficient of thermal expansion!), polished, and aluminized.

How can we make a big mirror?

Working with large chunks of glass can be challenging…

- + they are massive, placing substantial demands on telescope support structure
- + they can expand and contract as temperature changes, deforming their surfaces
- + they can be strongly affected by gravitational flexure (when pointing to different parts of the sky), deforming their surfaces

image credit: NASA

Solution # 1: spin-cast mirrors

Roger Angel (University of Arizona) pioneered the technique of spin-casting mirrors in a rotating furnace.

image credit: Steward Observatory

Rotation causes liquid glass to flow into a roughly parabolic surface, resulting in a mirror that is thinner and needs less polishing.

Solution # 1: spin-cast mirrors

The Richard F. Caris Mirror Lab at the University of Arizona (under the football stadium!) can produce up to 8.4m diameter mirrors.

The Vera C. Rubin Observatory has an 8.4m diameter mirror.

The Large Binocular Telescope has two 8.4m diameter mirrors.

The Giant Magellan Telescope will have seven 8.4m diameter mirrors comprising its primary aperture.

image credit: GMTO

Solution # 2: segmented mirrors

Jerry Nelson (University of California, RIP) pioneered the technique of using segmented mirrors to create large apertures, starting with the 10m Keck Telescopes.

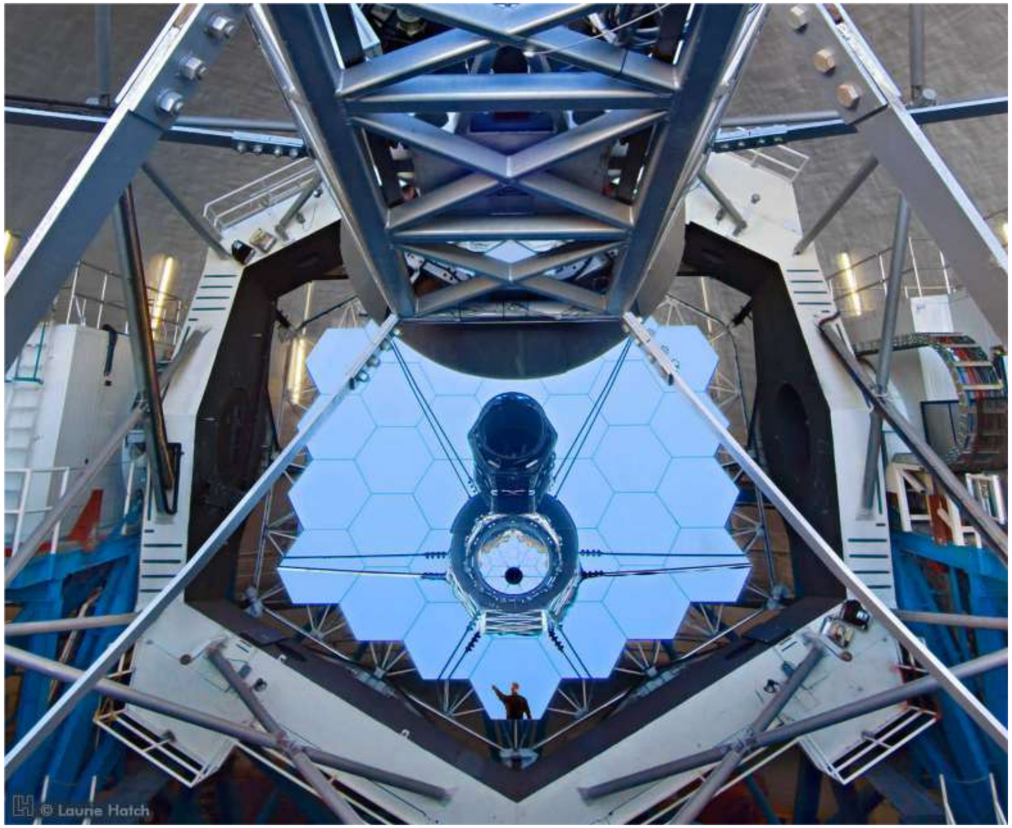
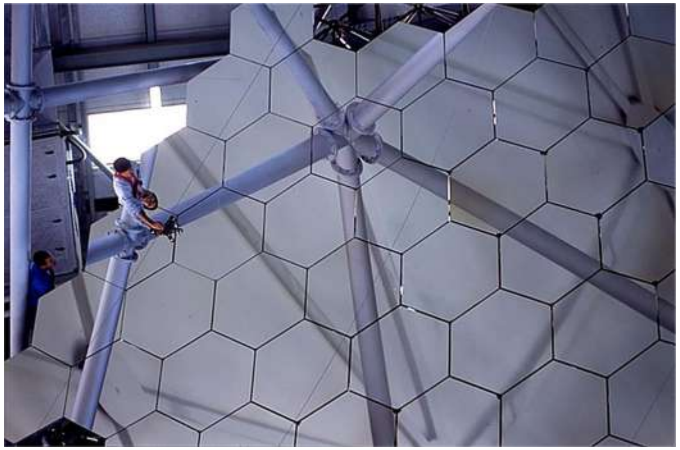


image credit: Laurie Hatch

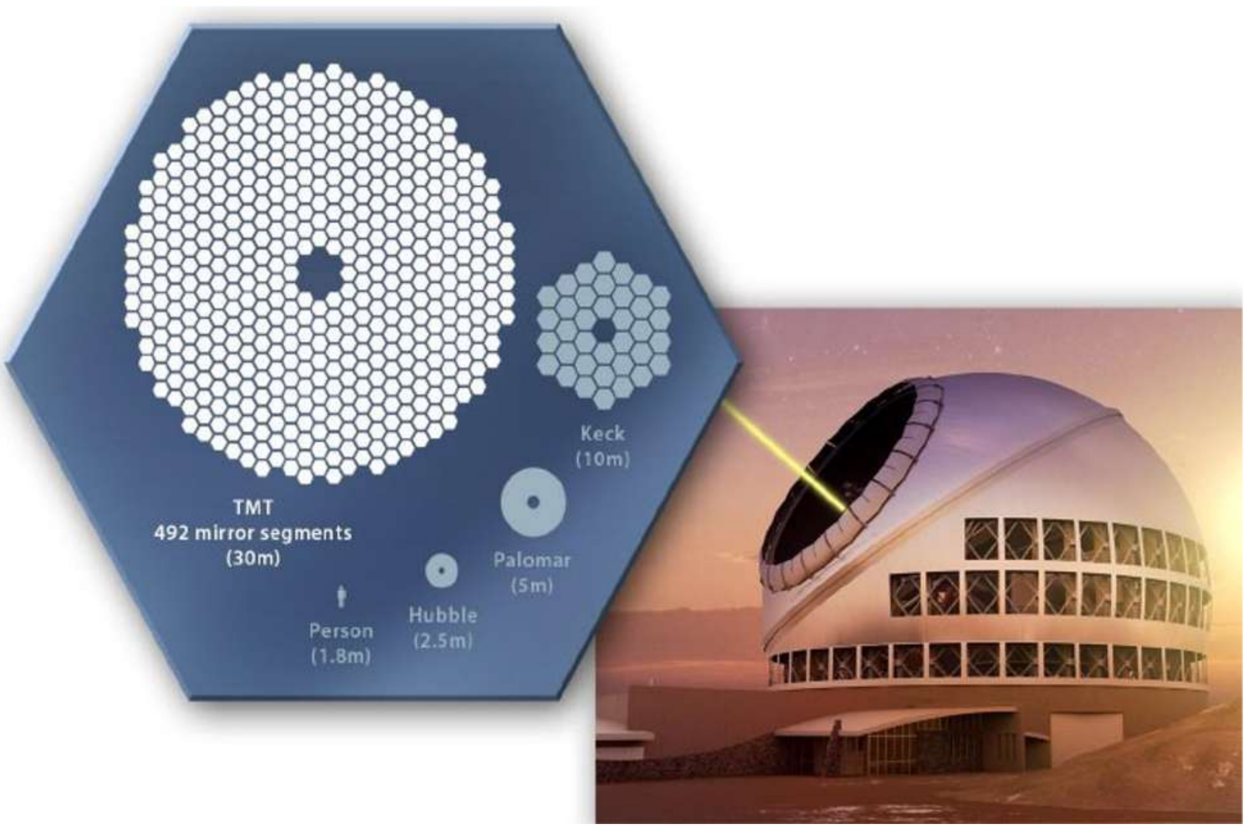
image credit: SALT



Segments can be thin and mounted on actuators that allow them to be realigned and compensated for flexure.

Solution # 2: segmented mirrors

Many of the next generation of ground (e.g., Thirty Meter Telescope) and space (e.g., *James Webb Space Telescope*) facilities have segmented mirror designs.



Video of mirror polishing one of the JWST mirror segments

Other telescope parameters

Telescope mounts can be equatorial, altitude-azimuth (alt-az), or fixed-altitude.

Equatorial mounts only require one drive motor during tracking, but are very massive – were used before the advent of computers (e.g., for Hale 5.1m, CTIO 4m, KPNO 4m), but not any more.

Alt-az mounts require two drive motors, and have trouble observing sources close to the zenith, but are lighter and more easily engineered – used for all fully steerable telescopes today.

Fixed-altitude mounts (HET, SALT) do not allow full sky access, but are cheaper. Targets can be tracked with the instrument package for ~ 1 hour exposures.

Other telescope parameters

Telescope enclosures (a.k.a. "domes") are now designed with an eye to optimizing seeing.

+ typically painted white so that daytime temperature remains cool, and there is not a lot of thermal contraction when nighttime observing starts up

+ increasingly designed with side vents to generate smooth air flow, which reduces the impact of ground-level turbulence

Instruments vs. telescopes

At optical/infrared wavelengths, there is a very strong distinction between a telescope that collects light and brings it to one or more foci, and an instrument that detects the light, often after filtering and/or dispersing it. (At radio wavelengths, this distinction is fuzzier – e.g., the Very Large Array has many antennas ~ telescopes, but only one correlator, which makes it ~ one instrument.)

+ a single telescope can have multiple instruments

+ multiple instruments that use the same focus can be swapped out for each other

+ a telescope can have facility instruments (typically built by the same institution(s) that paid for the telescope) and host guest instruments (built elsewhere) for visits

Key properties of an OIR instrument

What wavelength(s) does it work at – optical, near-IR, mid-IR?
(reminder: from ground, "optical" = 3000–10,000 Å, near-IR = 1–5 μm, mid-IR = 5–25 μm)

Is it an imager, a spectrograph, or both (integral field unit)?

If it's an imager: what is the field of view, and what filters are available for imaging?
+ filters can be broad-band (e.g., *UBVRI*), medium-band, or narrow-band (e.g., Hα and off-Hα for spectral line imaging)

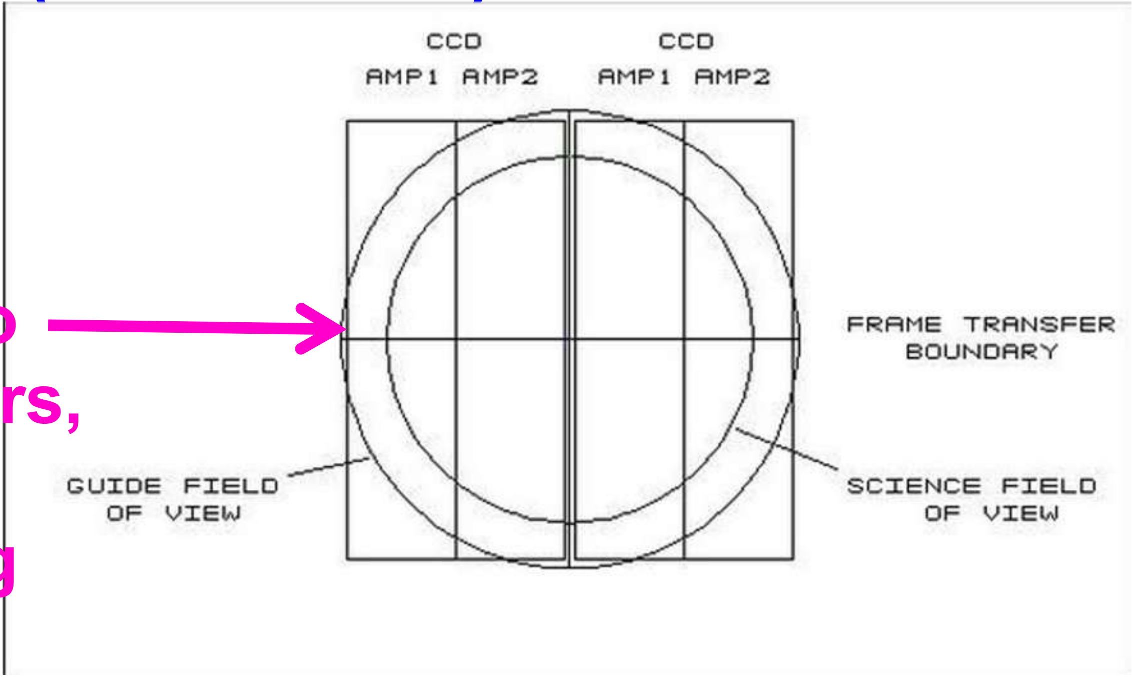
If it's a spectrograph: how many targets can be observed at once, and what is/are the possible spectral resolution(s)?
(reminder from Worksheet 2: $R = \lambda/\Delta\lambda$ = resolving power)

Example instrumentation suite

Southern African Large Telescope (SALT) instruments are described in the current "Call for Proposals" at http://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html

SALTICAM = optical camera with two CCDs (charge-coupled devices) covering an 8' diameter circular field of view, plus an eight-position filter magazine with 24 filters to choose from (3200–9500 Å)

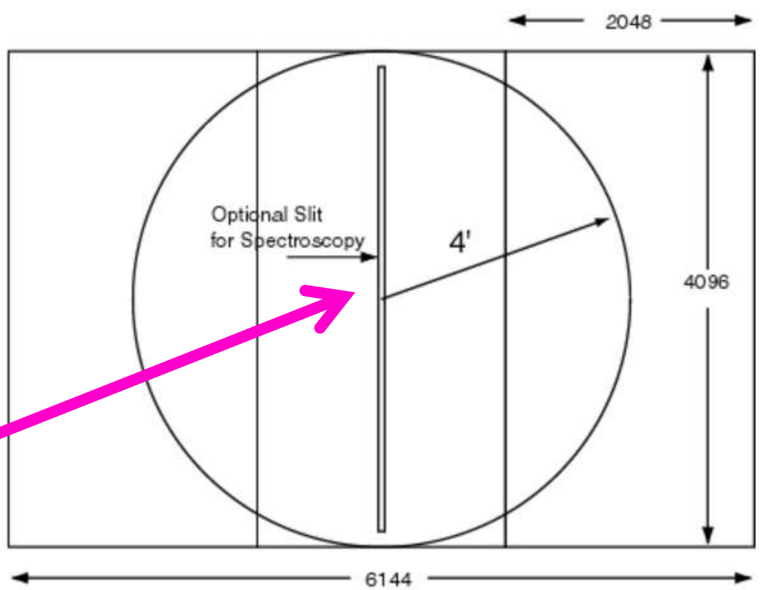
annulus is used to observe guide stars, which stabilize telescope tracking



Example instrumentation suite

Southern African Large Telescope (SALT) instruments are described in the current "Call for Proposals" at
http://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html

Robert Stobie Spectrograph (RSS) = optical (3200–9000 Å) instrument that can observe in long-slit (LS), multi-object spectroscopy (MOS), and Fabry-Perot (FP, an integral field technique) modes
+ for LS and MOS modes, R = 3000-9000 possible
+ MOS mode can observe up to 50 objects at once
+ for FP mode (4300–8600 Å only), R = 320–9000 possible

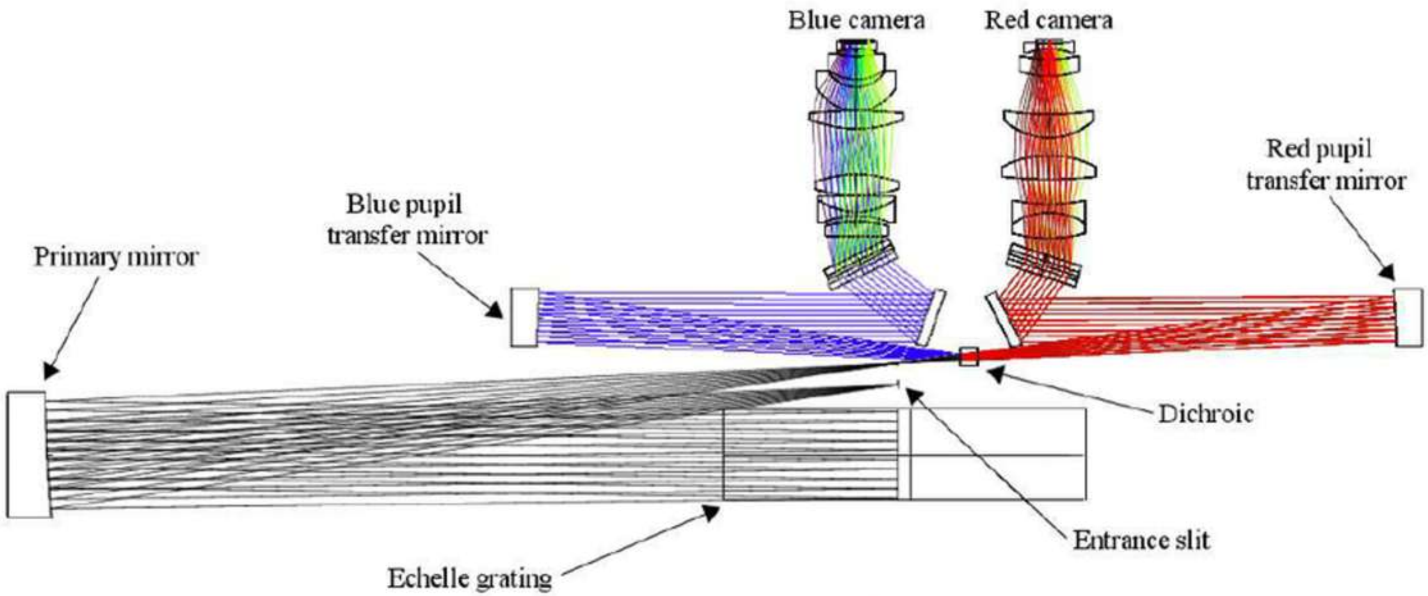


LS mode: only the "slit" sees sky

Example instrumentation suite

Southern African Large Telescope (SALT) instruments are described in the current "Call for Proposals" at http://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html

High Resolution Spectrograph (HRS) = optical (3700–8900 Å) single-object spectrograph that delivers *R* = 14000–65000 + good for targeting very bright objects (e.g., stars)



uses two cameras (CCDs) to cover full wavelength range

Fancier instruments possible...

The Very Large Telescope (VLT; actually, there are four!) at the European Southern Observatory (ESO) has a broad suite of optical, near-IR, and mid-IR instruments. One example: the K-band Multi Object Spectrograph (KMOS), which can do near-IR integral field spectroscopy for 24 targets simultaneously (using a set of 24 configurable arms with "pickoff mirrors").

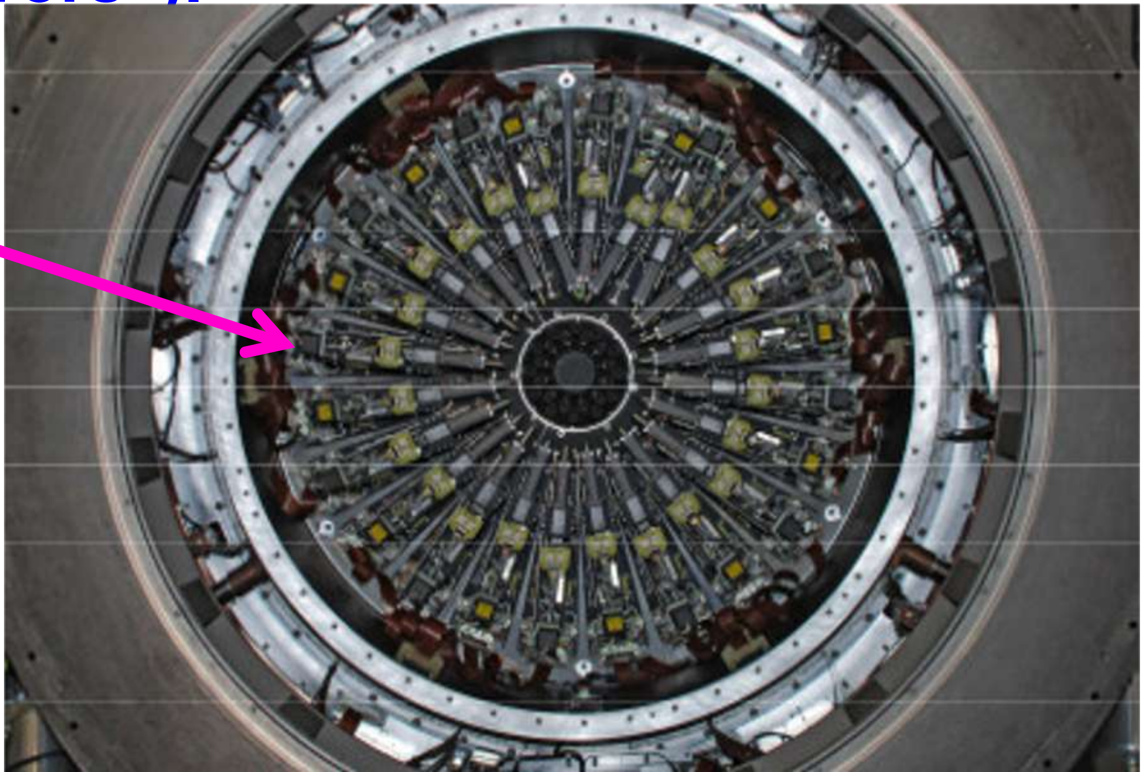


image credit: ESO

Detector = key part of any instrument

The **detector** is the part of an instrument that converts incoming photons into a signal that can be recorded and processed.

At optical/infrared (OIR) wavelengths, detectors are generally incoherent (no phase information captured), and can be **quantum** or **thermal** detectors.

In quantum detectors, individual photons interact directly with electrons in the detector. Examples: CCDs, eyes.

In thermal detectors, photons raise the temperature of a sensing element, and therefore change its electrical properties. Examples: bolometers.

CCDs

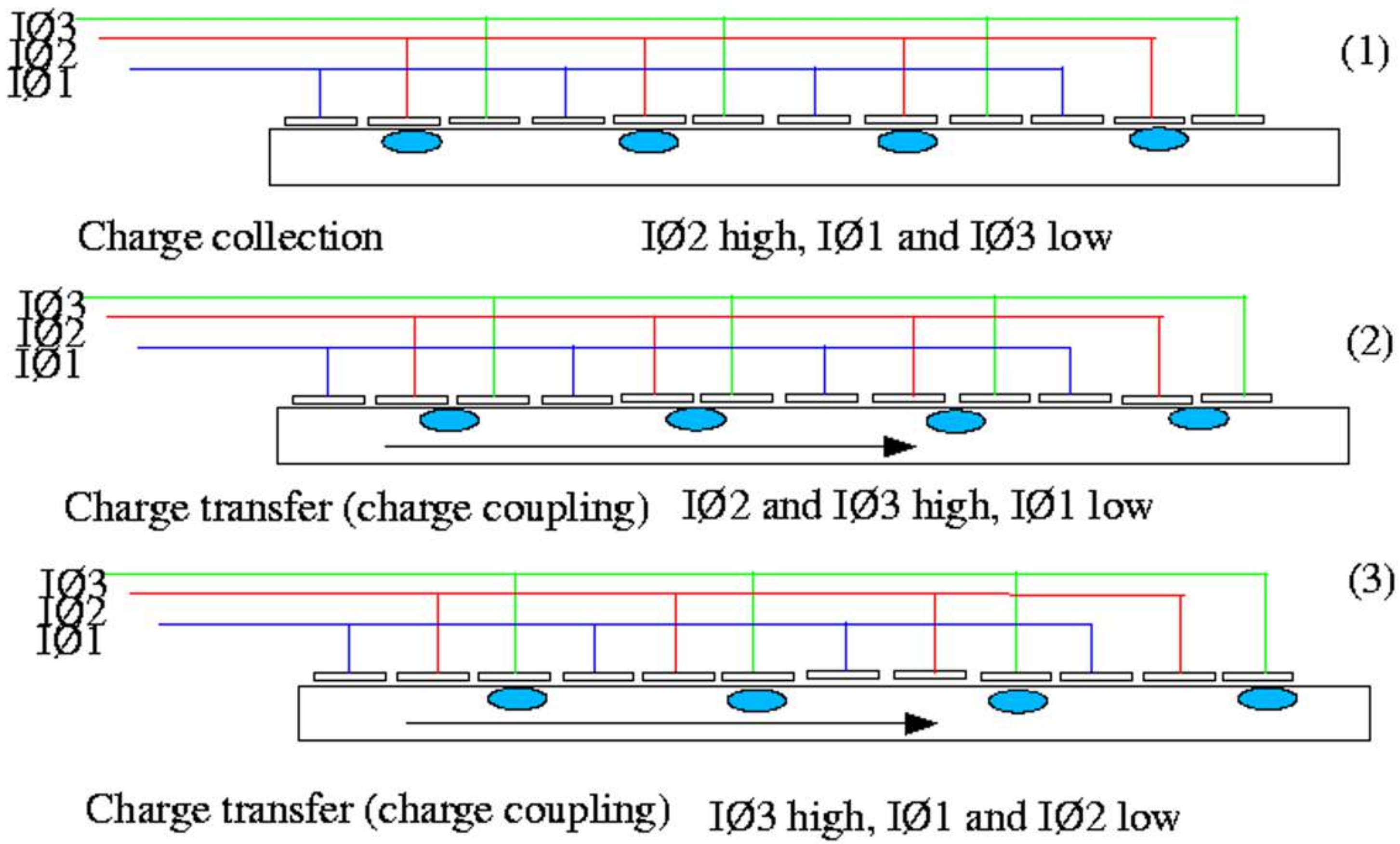
CCD (i.e., digital camera) technology revolutionized optical astronomy, allowing ever larger instruments (e.g., the Vera Rubin Observatory will have a camera with 3.2 billion pixels).

Basic idea: silicon wafer (with some Si atoms replaced by impurities) in which an incoming photon is converted into one or more electrons at its incident position

+ number of electrons proportional to intensity of photons at that position (i.e., response is linear)
+ electrons are held in place in individual spatial "pixels," defined by locations of charged electrodes that create potential wells
+ readout has to take place before wells are full

image credit: MSSL

Reading out a CCD



CCDs are read out along rows, with biases changed so that each pixel's electrons are shifted along separately. Implications: reads are destructive, and can take several minutes to complete – so impact observing strategy.

Infrared detectors

At infrared wavelengths, silicon no longer works as a detector material, so we need to use other materials instead. Three workhorse detector types:

+ $Hg_xCd_{1-x}Te$ “mercadtel” detectors, most common technology for 1–2.5 μm

+ InSb “insbee” detectors, which work out to 5 μm

+ GaAs (gallium arsenide) detectors, sensitive into mid-IR

IR detectors need to be operated at low (liquid nitrogen) temperature, to prevent thermal excitation of electrons.

Each pixel is read out separately (with Si-based electronics), so reads are fast and nondestructive.

An extra challenge for IR observing

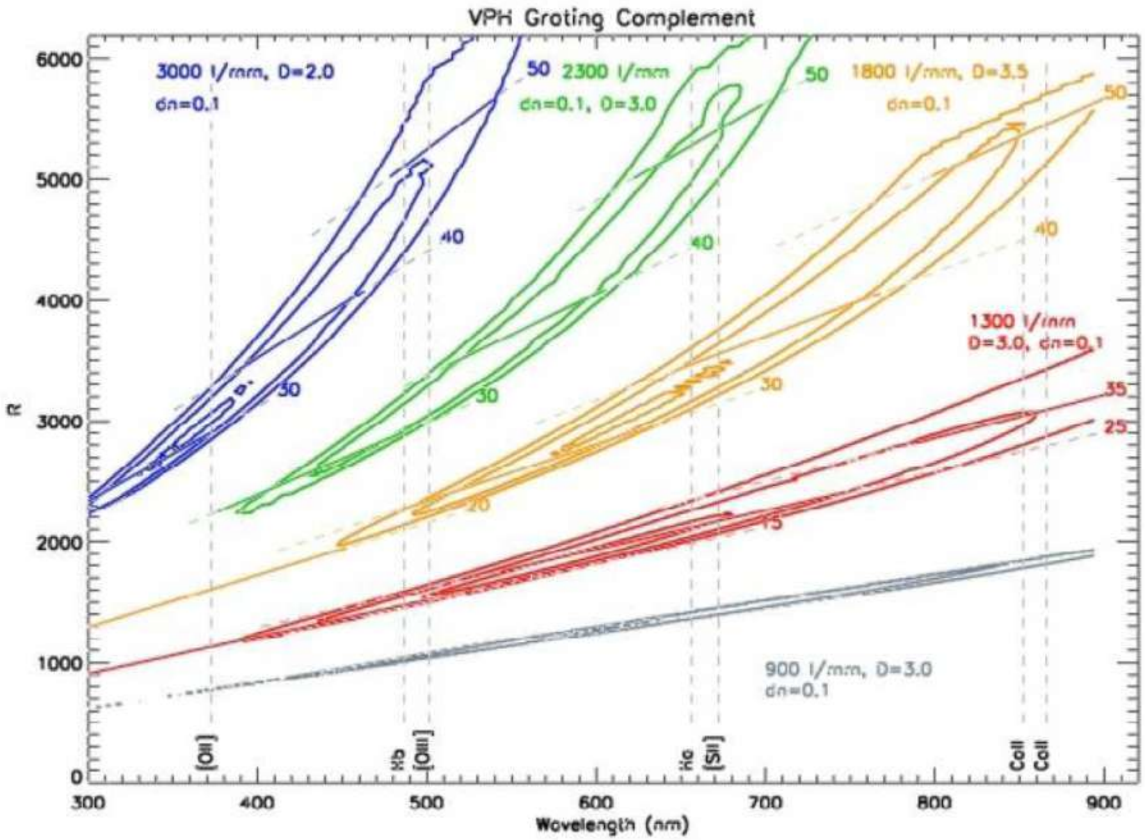
Even if we cool the detector down to low temperatures,
there will still be lots of thermal photons from the telescope (mirrors etc.) and the sky that can mimic photons from an astronomical target.

Strategy for getting around this: chopping + nodding.

- + chopping = rapidly switching the telescope's secondary mirror between an on-target and an off-target position (1–20 Hz), and taking the difference between these two signals – this removes sky background
- + nodding = moving the entire telescope every 10–120s so that the chop position that was previously on-target is now off-target and vice versa – this removes telescope/optics background

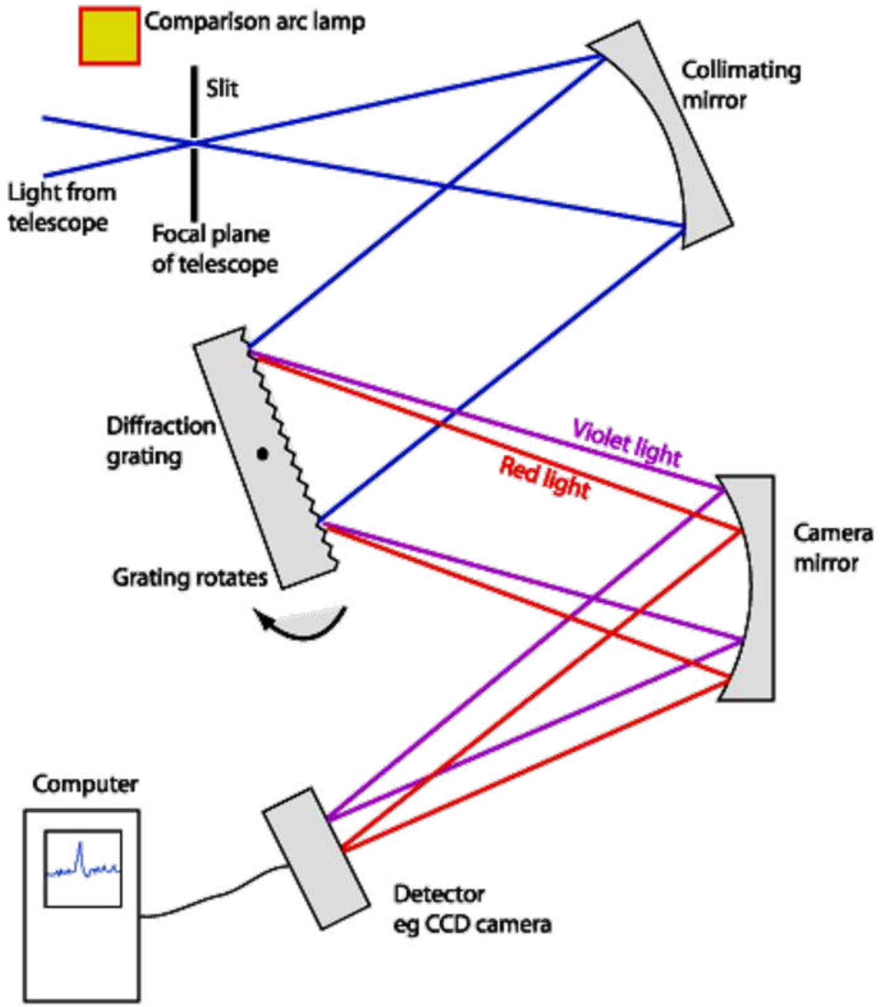
Spectroscopy

For spectroscopy, the key additional challenge is to disperse light into its constituent wavelengths before it gets to the detector (whether optical or infrared). This is most often, though not always, done with a diffraction grating.



Available diffraction gratings for SALT/RSS

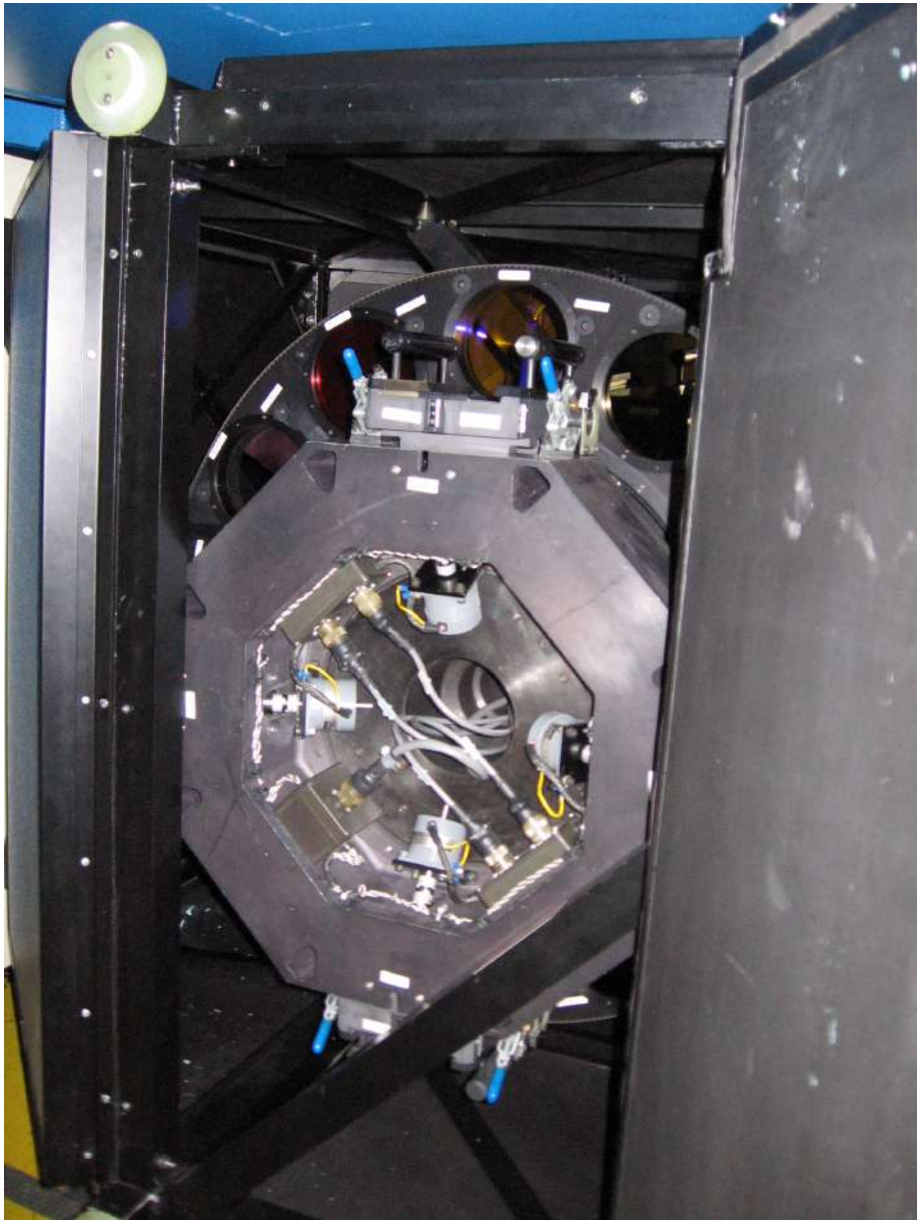
Basic Spectrograph Design



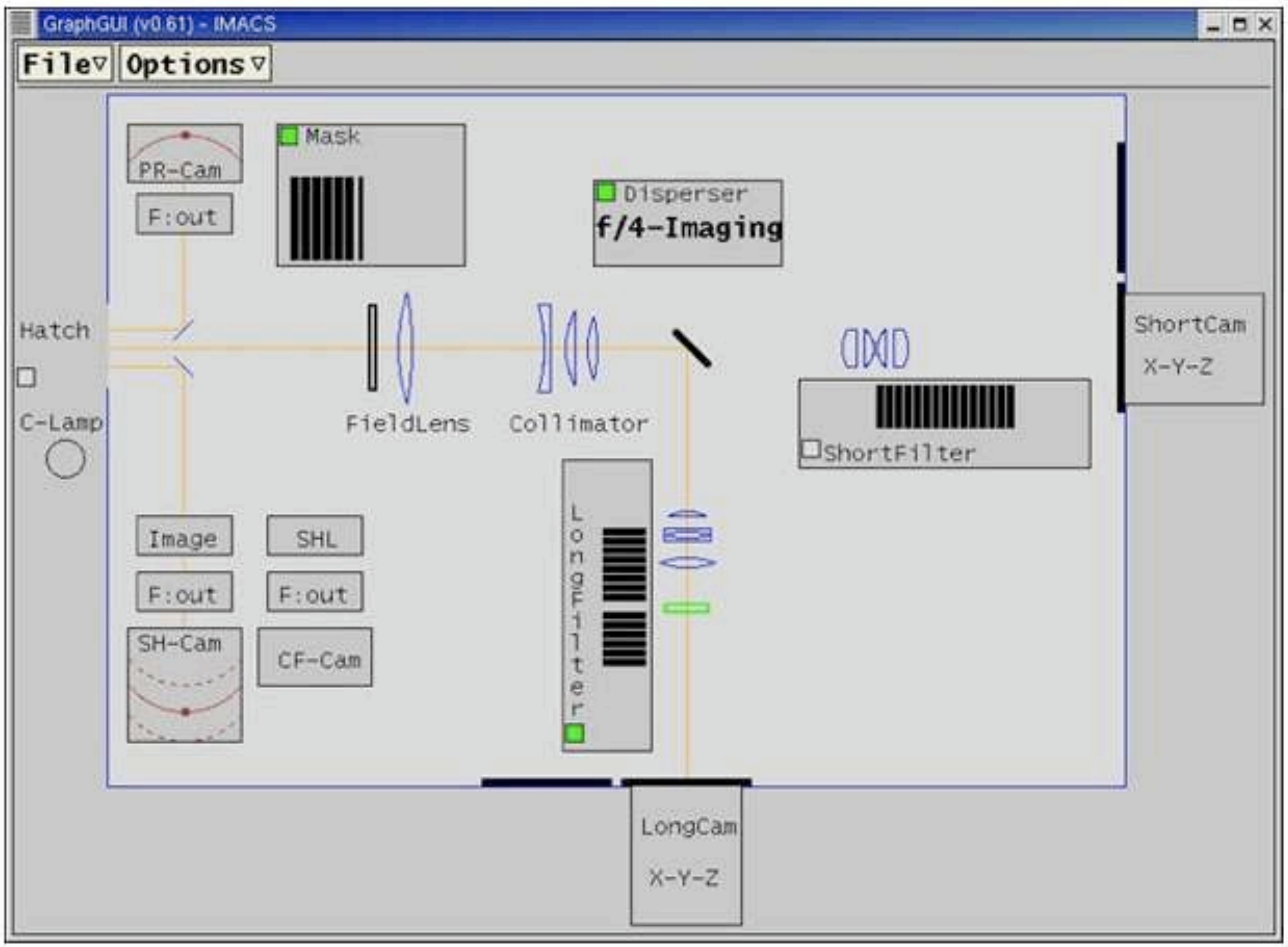
A Schematic Diagram of a Slit Spectrograph

Gemini Multi-Object Spectrograph: Slitmasks and fibers

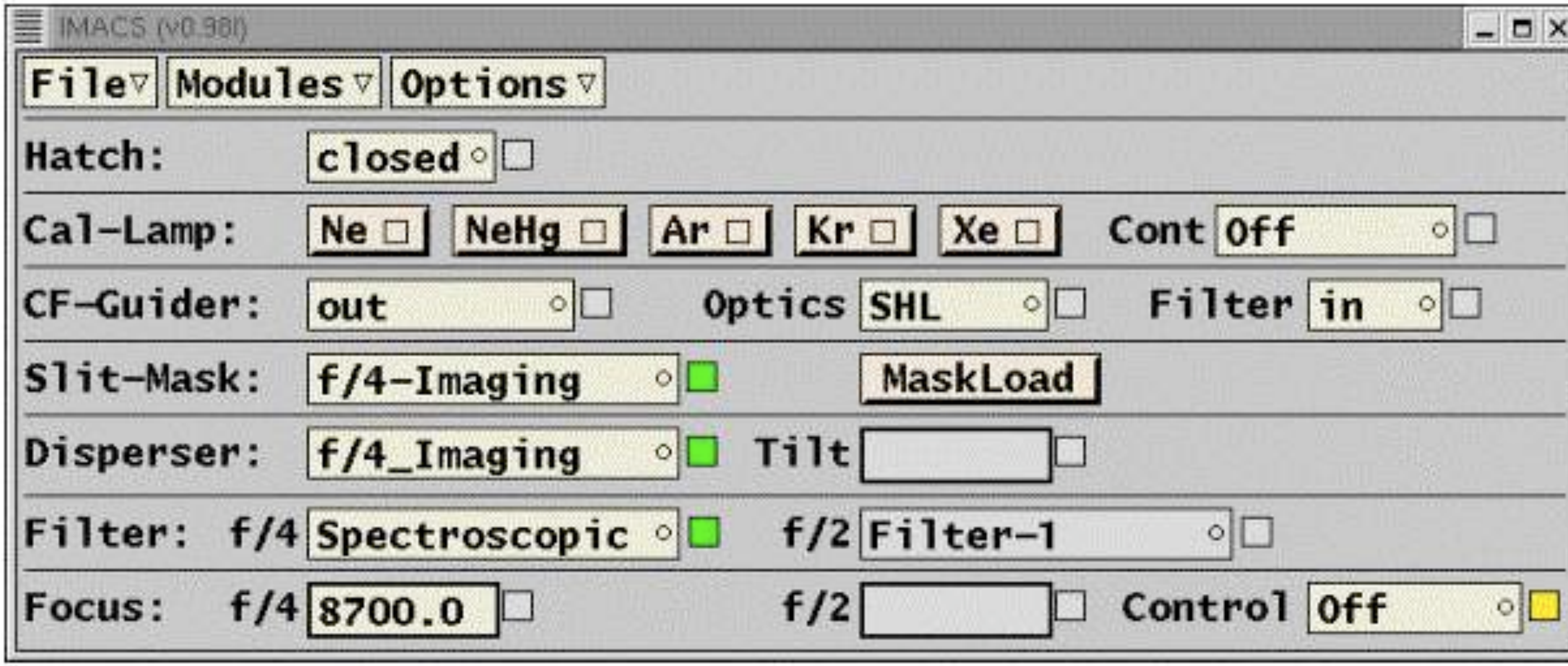
Gemini Multi-Object Spectrograph: Gratings, Filters, and Camera



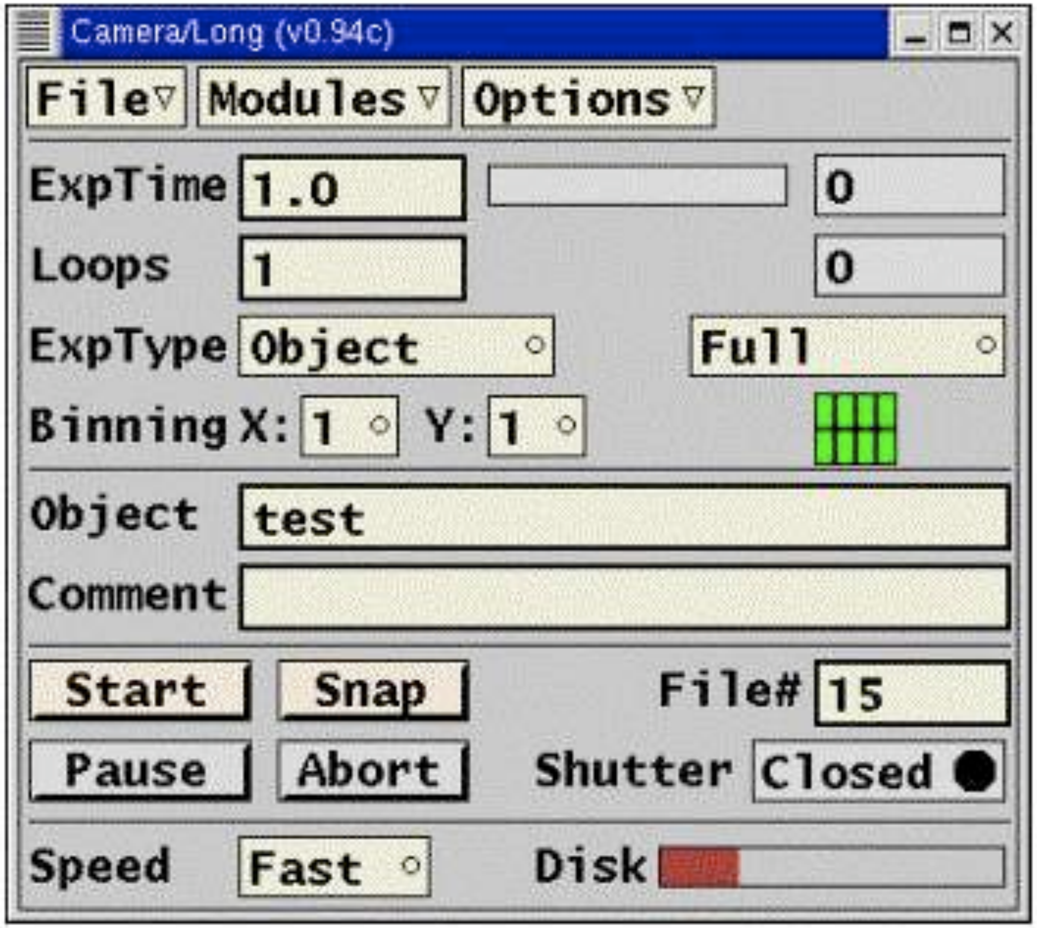
GUIs for IMACS spectrograph on Magellan



GUIs for IMACS spectrograph on Magellan



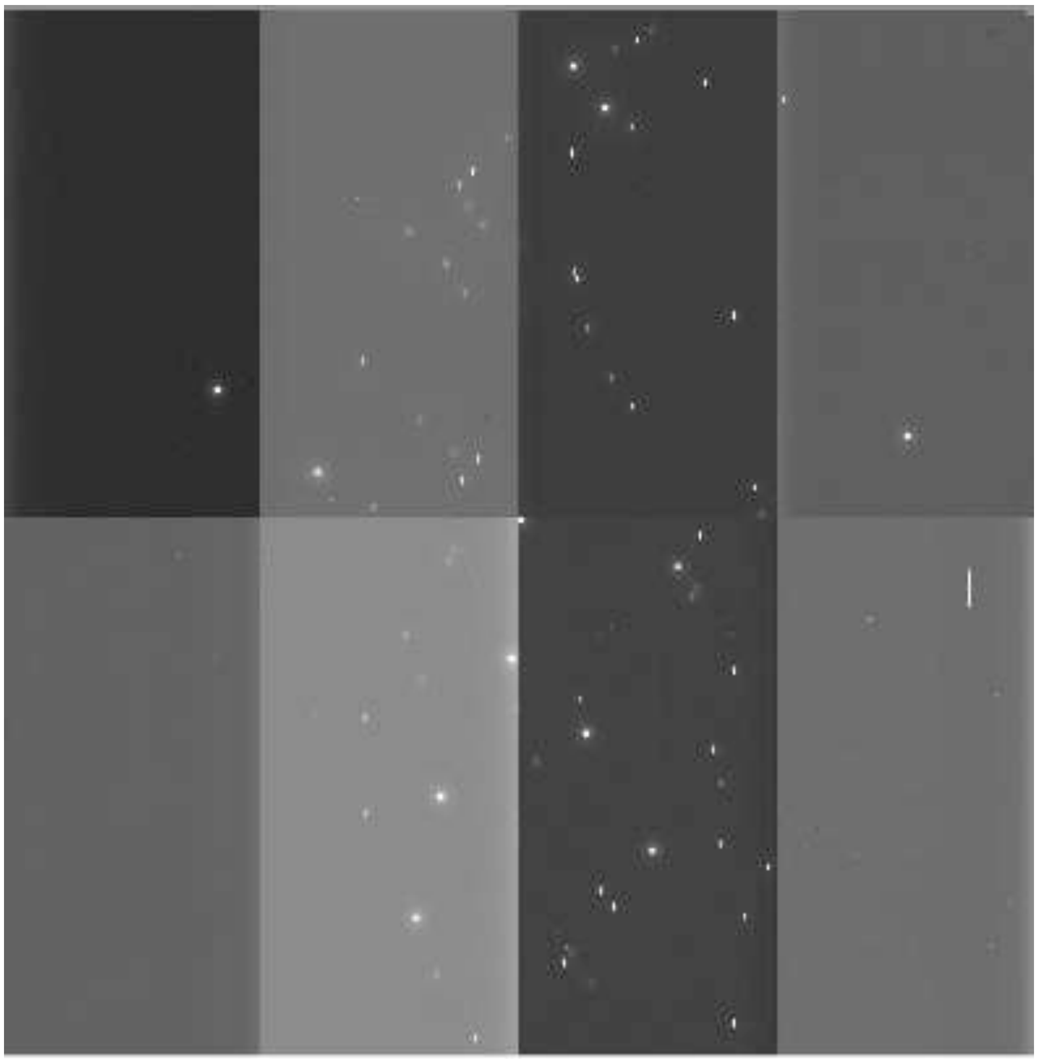
GUIs for IMACS spectrograph on Magellan

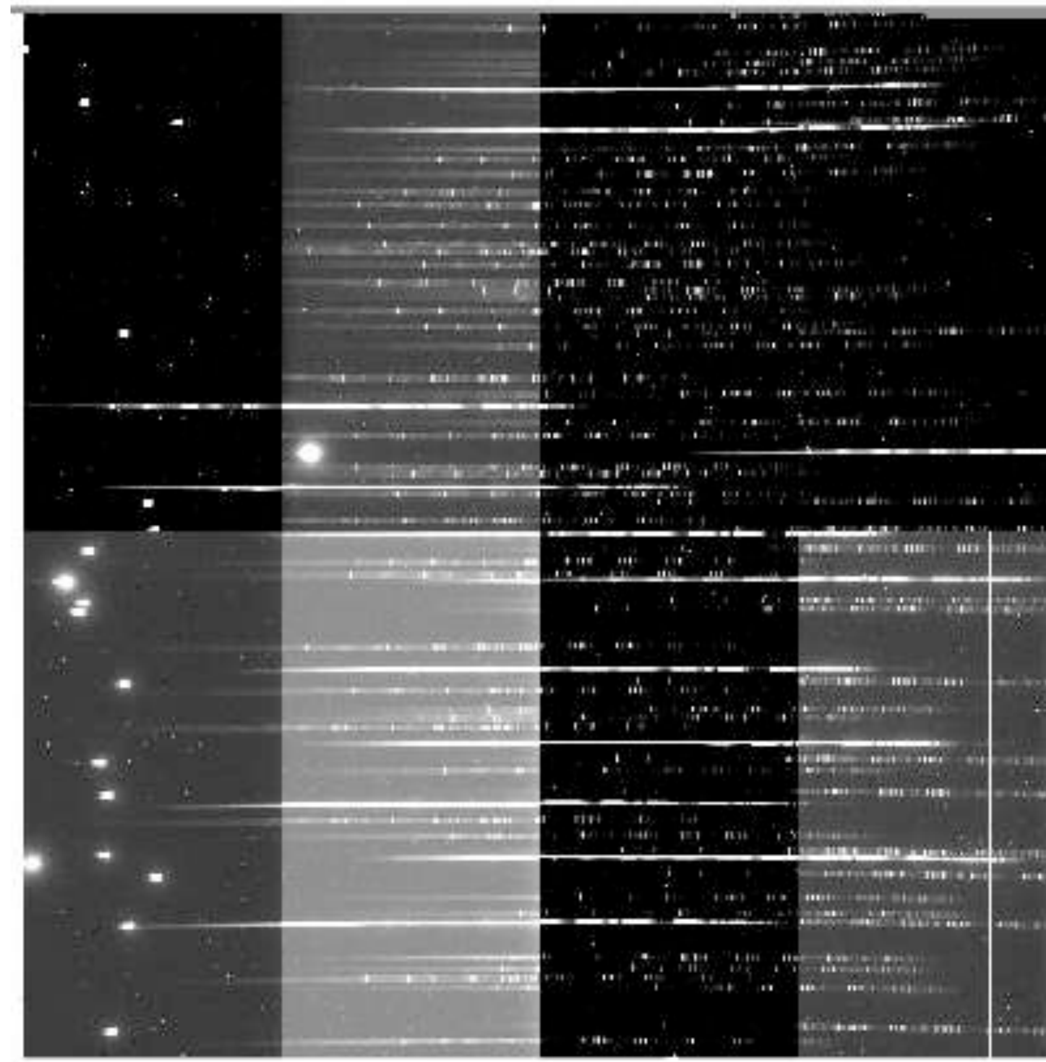


The Magellan Control Room

Photo by S. Virani

Raw IMACS data:
mask image → 2-d spectrum





Data Equation: Spectroscopy

$$F_\lambda(\mathbf{r},\lambda,t) = \left[\sum_j f_{\lambda,j}(\lambda,t) A_{tel} T_{atm}(\lambda,t,X) PSF(\mathbf{r}(\mathbf{\Omega}_j(t)),\mathbf{r},\lambda,t) + B(\mathbf{r},\lambda,t)\right] T_{tel}(\lambda,\mathbf{r}) T_{qe}(\lambda,\mathbf{r}) T_{filt}(\lambda,\mathbf{r})$$

Spectroscopy involves dispersion of photons from unmasked region, resulting in a convolution of position **r** and wavelength λ reaching position **R** on detector

$$F(\mathbf{R},t) = \int_\lambda \int_\mathbf{r} F_\lambda(\mathbf{r},\lambda,t)\, \delta(\mathbf{R} - \mathbf{R}(\mathbf{r},\lambda))\, d\mathbf{r}\, dt$$

Yields F_λ[ergs/s/Å] received at location **r** on focal plane.
Number of photoelectrons in image i at pixel (x,y) results from dividing by energy per photon,
integrating over time and pixel area,
adding bias, dark current, fringing, cosmic rays, and bad pixels

$$N_i(x,y) = \int_t \int_{pixel} \frac{F(\mathbf{R},t)}{(hc/\lambda)} d\mathbf{r}\, dt + bias(x,y) + Dark * t_{exp} + Fr(x,y) t_{exp} T_{qe}(x,y) + CR(x,y,i) + BP(x,y)$$

Data Reduction Pipeline: Spectroscopy

$$N_i(x,y) = \int_t \int_{pixel} \frac{F(\mathbf{R},t)}{(hc/\lambda)} d\mathbf{r}\, dt + bias(x,y) + Dark * t_{exp} + Fr(x,y) t_{exp} T_{qe}(x,y) + CR(x,y,i) + BP(x,y)$$

- Mask and replace bad pixels and cosmic rays
- Subtract bias using overscan/zeros
- Subtract dark current
- Flat-field by dividing by domelamp or twilight "flat" image
- Subtract fringes using "fringe template"
- Assume F(**R**,t) constant over pixel, t → F(**R**,t_i)

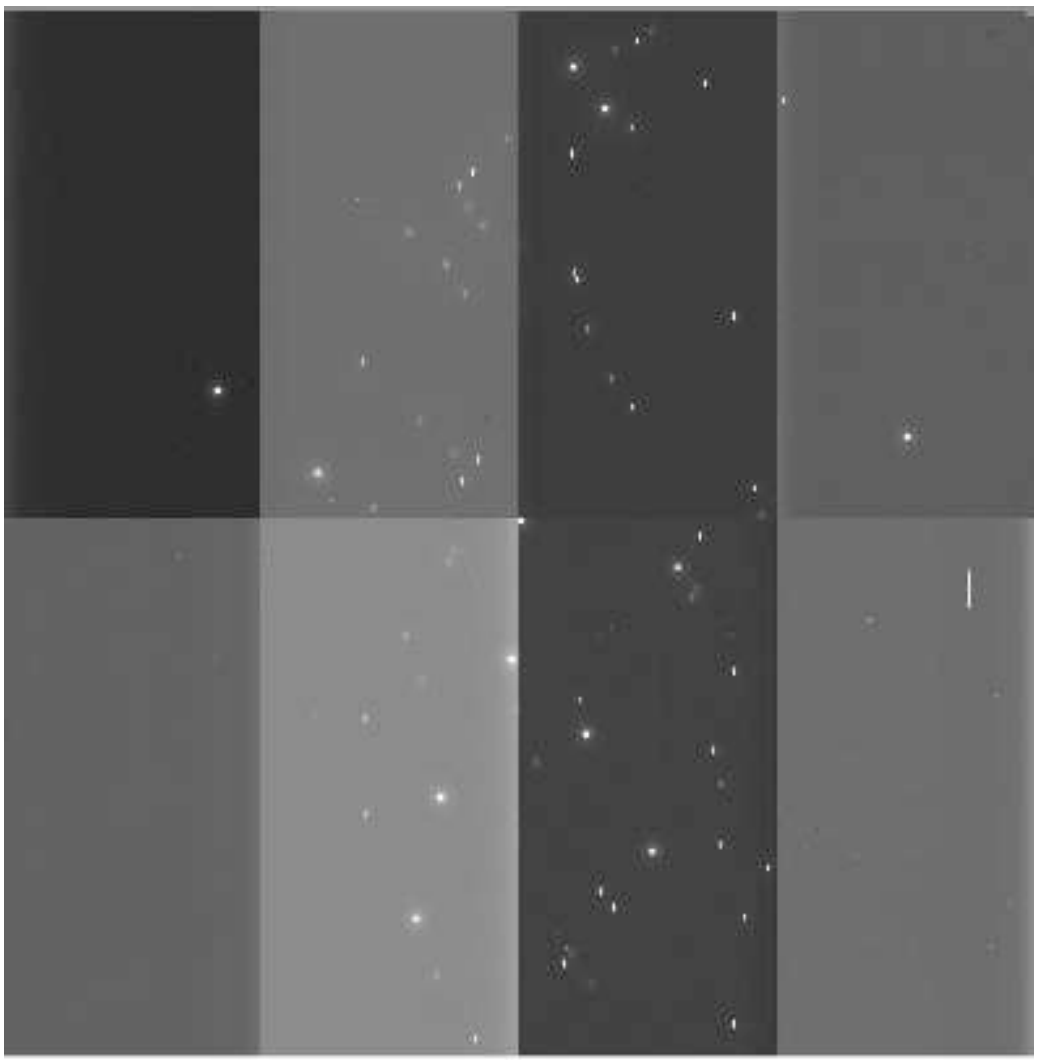
$$F(\mathbf{R},t) = \int_\lambda \int_{\mathbf{r}} F_\lambda(\mathbf{r},\lambda,t)\, \delta(\mathbf{R} - \mathbf{R}(\mathbf{r},\lambda))\, d\mathbf{r}\, dt$$

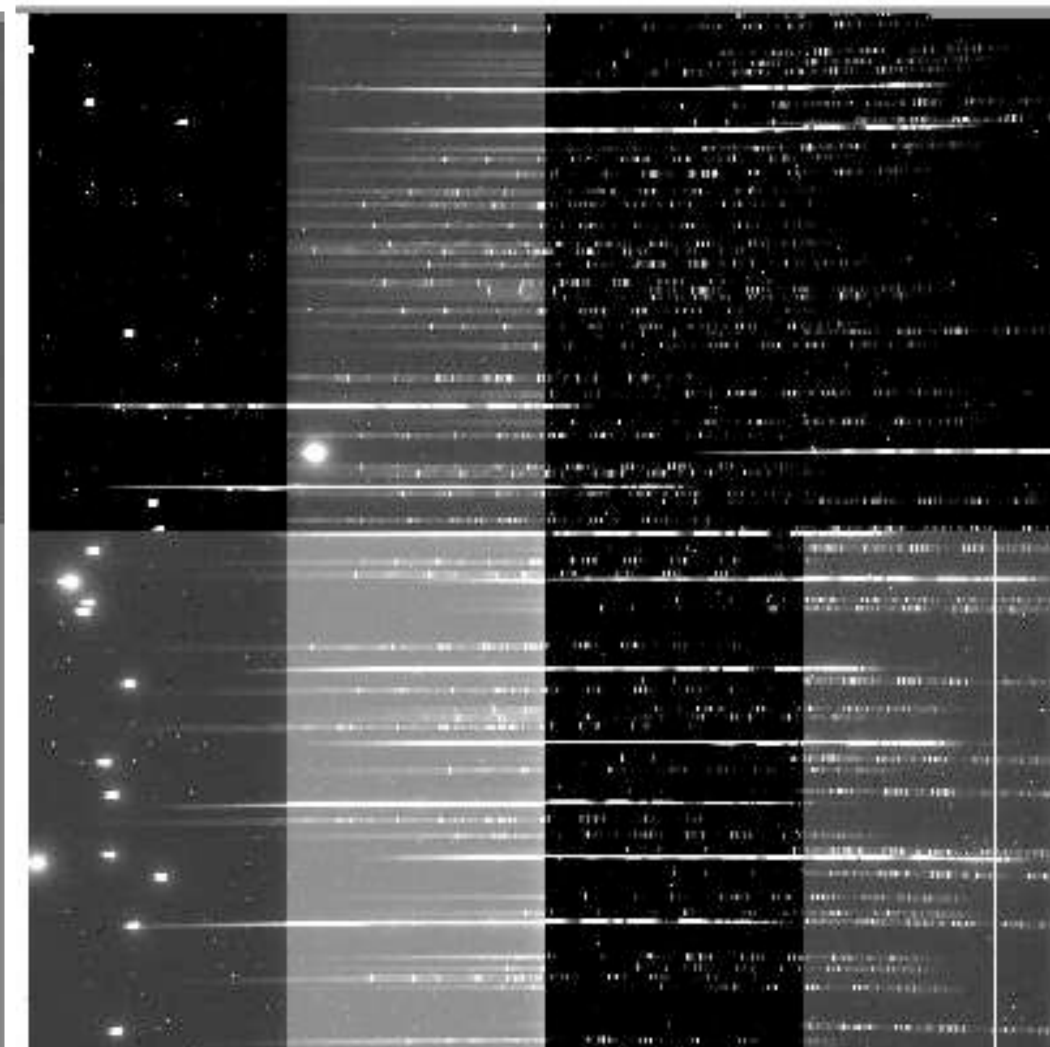
- Using approximations **r**(**R**), λ(**R**), deproject to get F_λ(**r,** λ,t_i)

$$F_\lambda(\mathbf{r},\lambda,t) = \left[\sum_j f_{\lambda,j}(\lambda,t) A_{tel} T_{atm}(\lambda,t,X) PSF(\mathbf{r}(\mathbf{\Omega}_j(t)),\mathbf{r},\lambda,t) + B(\mathbf{r},\lambda,t)\right] T_{tel}(\lambda,\mathbf{r}) T_{qe}(\lambda,\mathbf{r}) T_{filt}(\lambda,\mathbf{r})$$

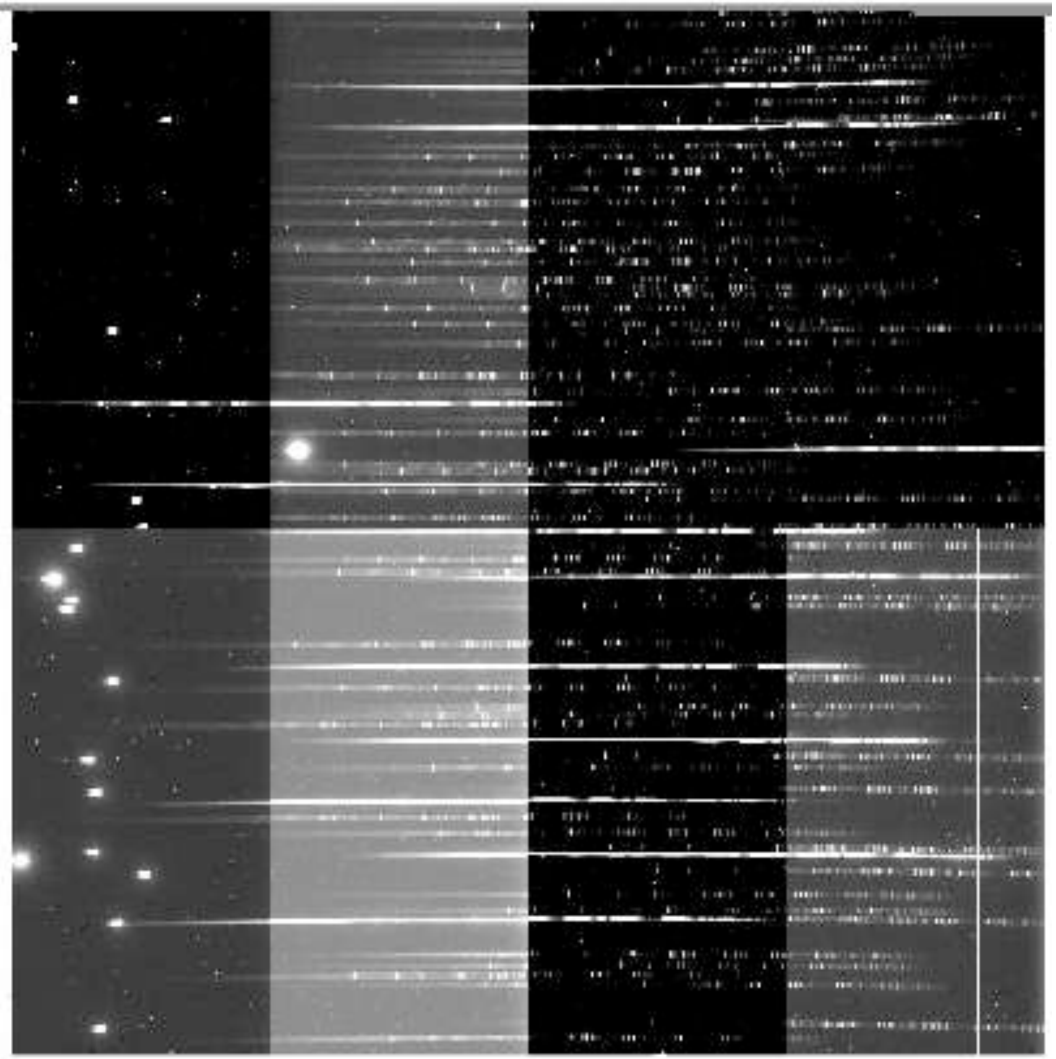
- Subtract background (e.g. a b-spline in position, wavelength)
- Combine multiple exposures, ignoring masked pixels
- Flux calibration yields just the unmasked PSF-convolved sources
- Extract object spectrum (e.g. IRAF apall)

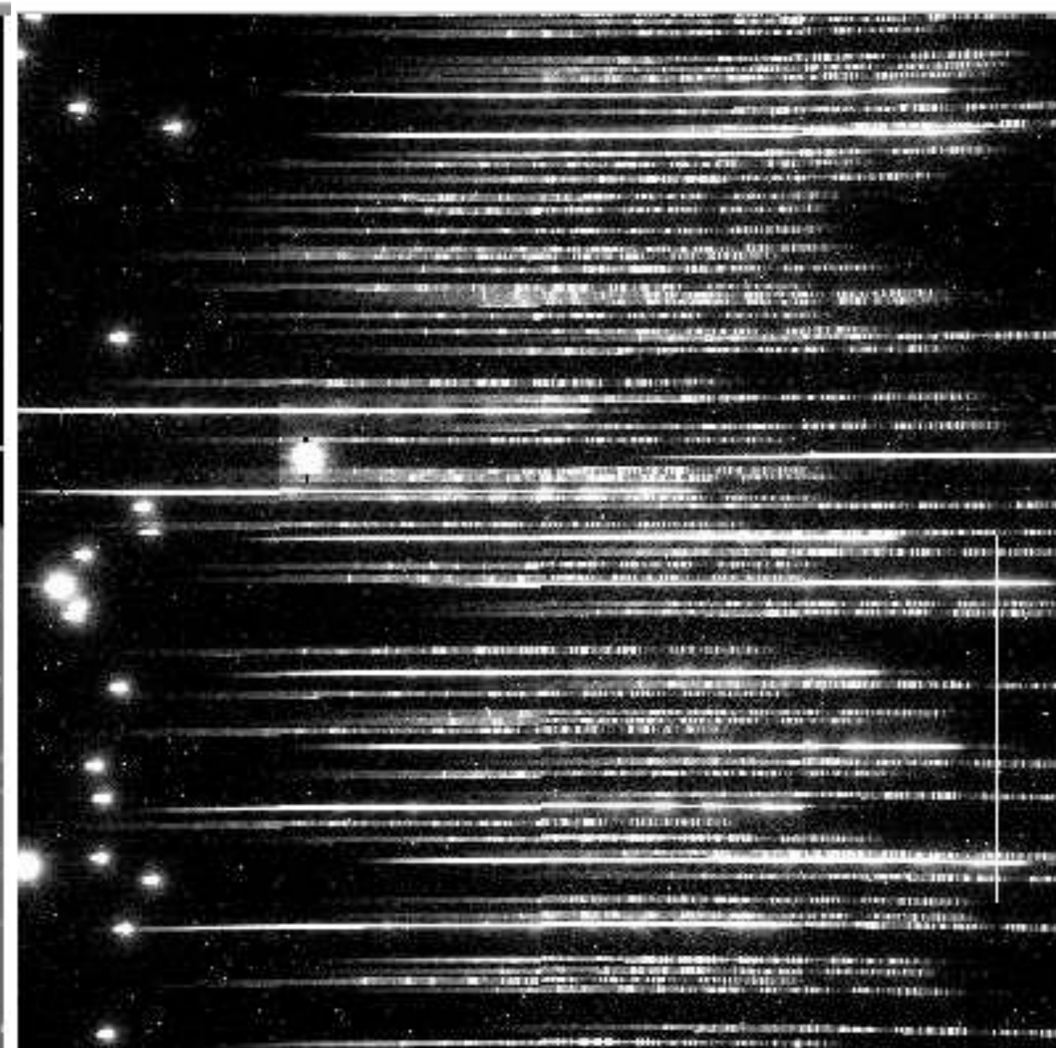
Raw IMACS data:
mask image → 2-d spectrum



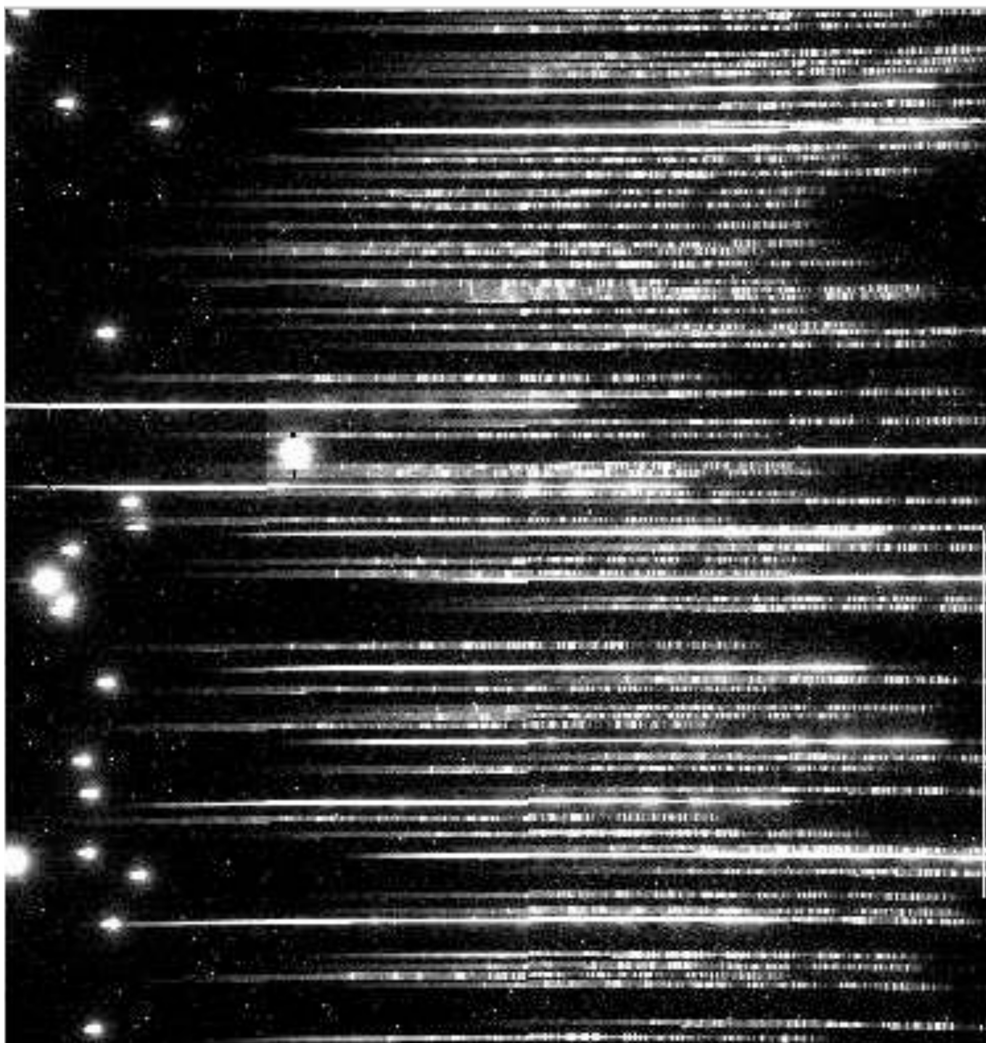


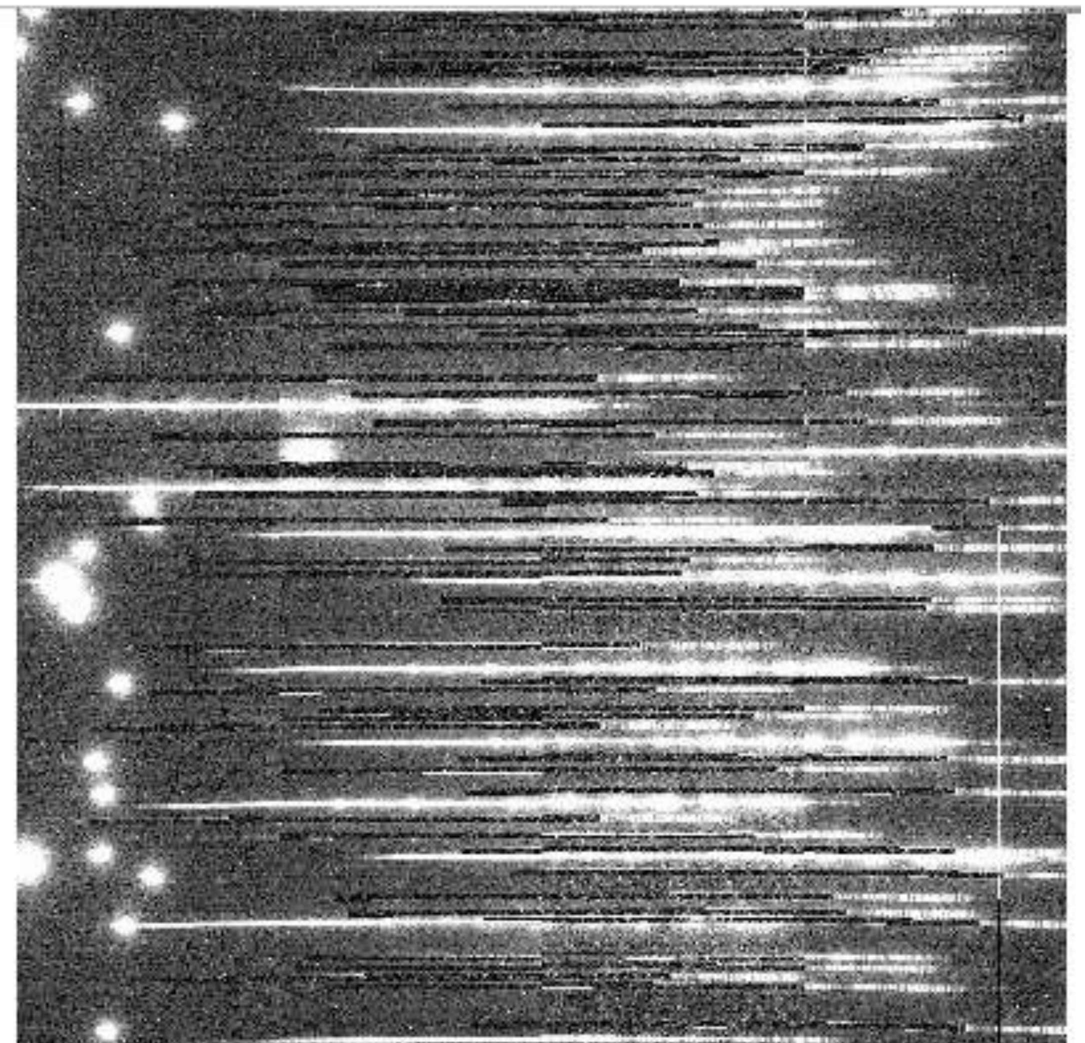
COSMOS Pipeline: 2-d spectrum → after bias subtraction and flat-fielding



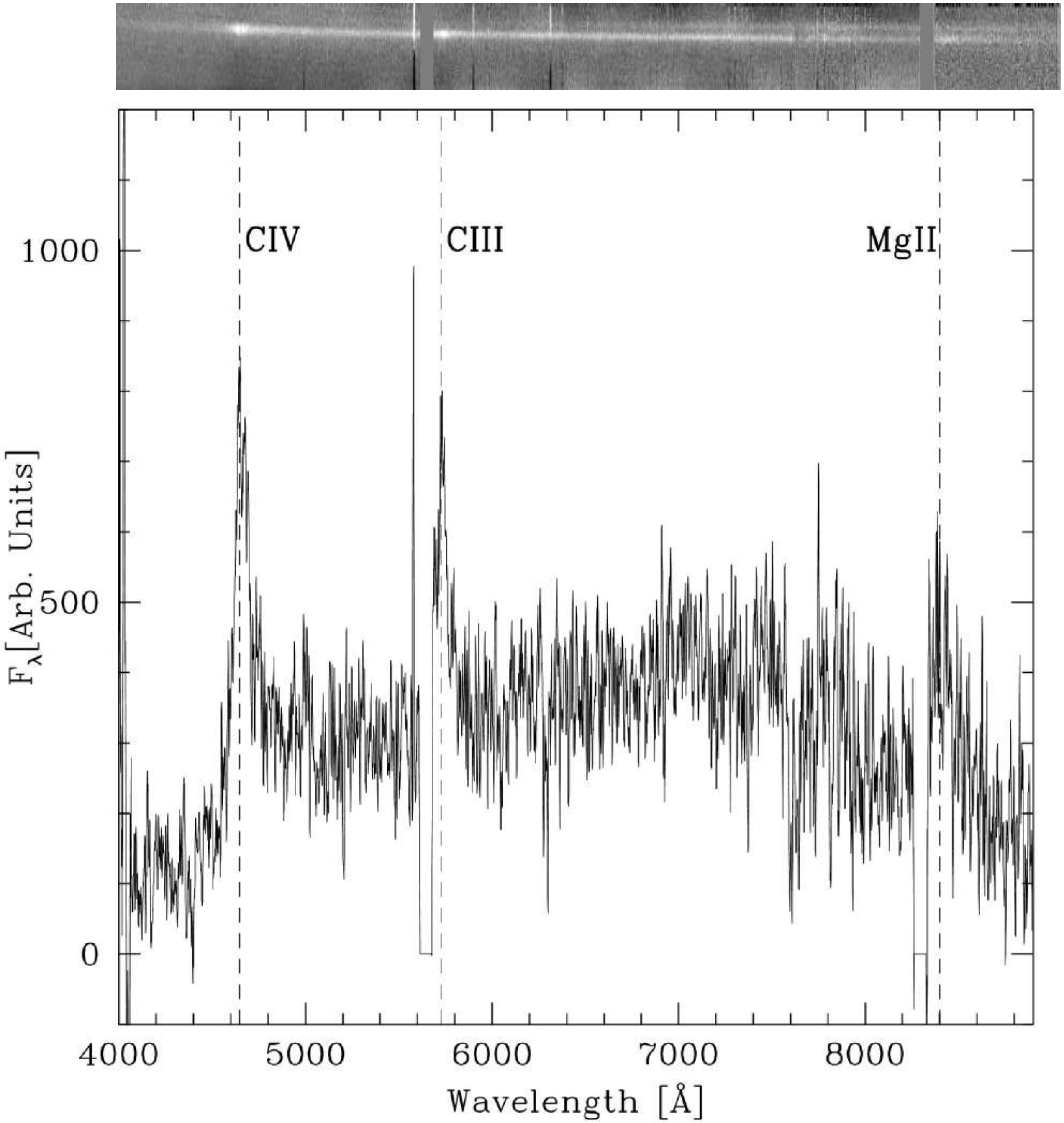


COSMOS Pipeline: after bias/flat→ after sky subtraction





IMACS Spectrum



Vmag~22.5