Advances in Infrared Instrumentation

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Look at the past, present, and future of infrared instrumentation through the lens of high resolution spectroscopy.

We are lazy.

Most of the gains we have made in the past
30 years come from somebody else doing the hard work.

1. Detectors – first and foremost
2. Image Quality
   - General
   - Adaptive optics
3. Bigger and lower background telescopes.

The future relies on work in these areas as well.

Detectors

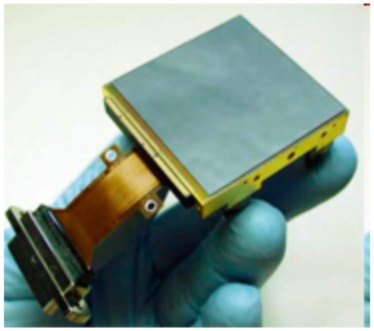
Detectors have improved in multiplex advantage, sensitivity, and uniformity.

Ground-based R=50,000-100,000 spectrographs have similar background environments to space based imagers in the mid-IR and lower backgrounds in the near-IR. These instrument benefit enormously from space-quality detectors.

How many megapixels did the camera have that I used when I was Giovanni's student in 1979?

10^{-6} !!!

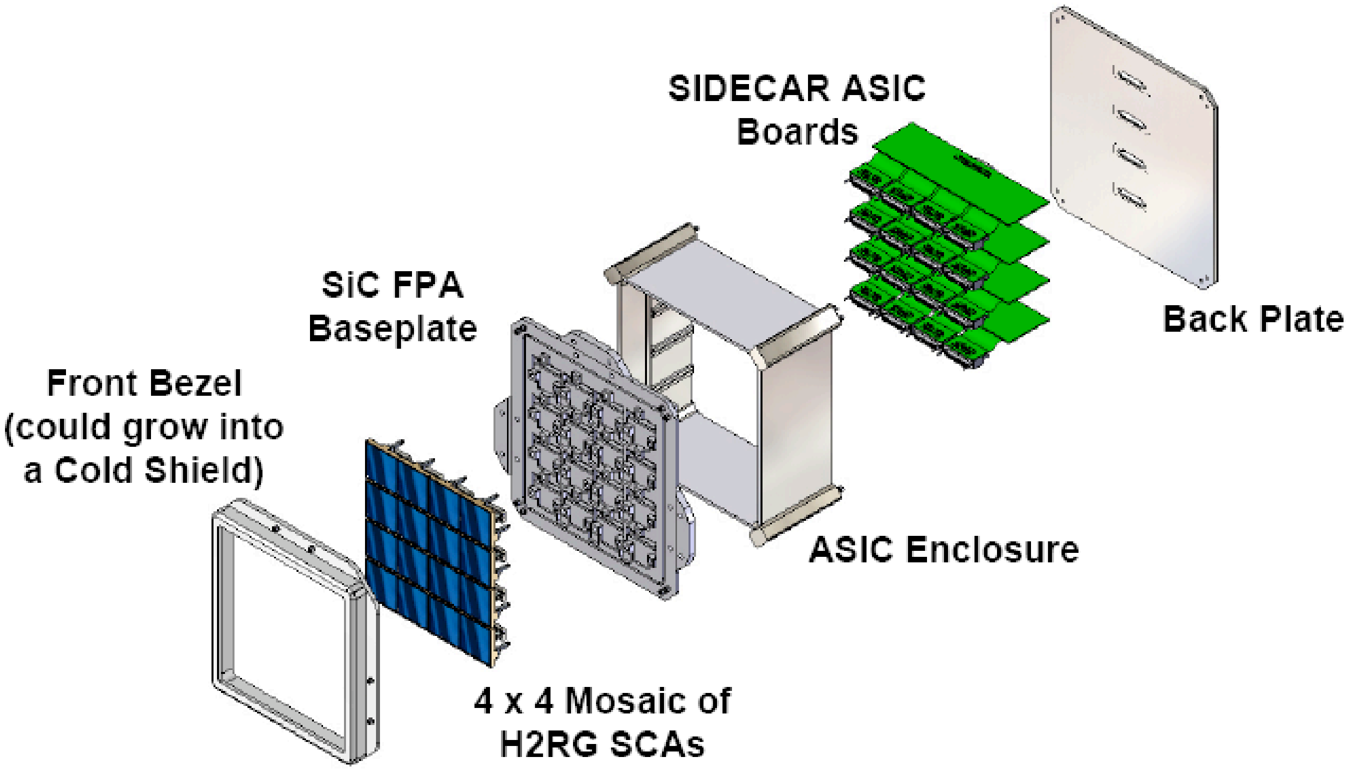
The current state of the art is beyond that by
a factor of 10 MILLION!!



Teledyne 2048 x2048 HgCdTe array.
QE ~80%, read noises ~5 e^-
dark currents $<10^{-2}$ e/s
Good uniformity.
Some instruments contain 4 or more devices.

The individual pixels are vastly better than the detectors we had available 30 years ago.

Focal Plane Array Package – Example 4×4



SIDECAR ASIC Boards

Back Plate

SiC FPA Baseplate

Front Bezel (could grow into a Cold Shield)

ASIC Enclosure

4 x 4 Mosaic of H2RG SCAs

Image Quality

For a high resolution spectrograph, one important figure of merit is the resolving-power slit-width product, Rθ.

For a given grating spectrograph on a given telescope, this quantity is conserved, as long as you don't try to exceed the diffraction limit in either quantity:

$R\theta = R_{Diff} q_{diff} = 2n(W/D)\tan\beta$

n is the refractive index of the medium

W the width of the spectrograph collimated beam

D the telescope diameter

β the incidence angle on the grating.

Background

Back in the day, nobody cared about background in the near-IR. Eventually (circa 1975), the imaging people began to care (i.e. detectors improved), then the low resolution spectroscopists. By now, even high resolution spectroscopists care when you get past 2.2 μm.

The background reaching your detector goes as

$n = (A\Omega/h)\varepsilon \; (B_\nu(T)/R)$ photons/second/resolution element

where

Ω is the solid angle of a spatial/spectral resolution element

ε is the emissivity of the warm optics and atmosphere

Let’s look at the effects of improvements

Image Quality

We have gone from routinely having 2” image quality to routinely having 0.7” image quality.

$R\theta = R_{Diff}\theta_{diff} = 2n(W/D)\tan\beta$

For a fixed instrument, this means we get 3 times as much throughput when the slit is small.

It means we can get the same throughput on a 3x larger telescope (so sensitivity continues to improve as D^2).

It means we can get the same throughput at 3x the spectral resolution.

With AO, things can get even better- It’s magic, instruments don’t grow at all!! (The lazy instrumentalist’s dream solution).

$n = (A\Omega/h)\varepsilon\ B_\nu(T)/R$ photons/second/resolution element

Background

It was recognized long ago that careful design could lower **ε** from the 0.5 that was typical of optical telescopes to 0.1 or even less. There are a number of modern telescopes that do this.

The improvement of image quality also lowers the background by reducing the Ω in the AΩ term. For fixed conditions, the smaller slits (and smaller spectral images) allowed by the factor of 3 in image quality, lower the background by a factor of 9.

Background: The Importance of Adaptive Optics on GSMT's

Right now, adaptive optics is roughly a wash for spectroscopic sensitivity in the background limit.

$$\frac{(S/N)_{AO}}{(S/N)_{NS}} = \frac{\eta_{strehl}}{\eta_{slit}} \frac{(1-(\epsilon_{tel}+\epsilon_{slit}))}{(1-\epsilon_{tel})} \left[(\Omega_{slit}/(m\Omega_{diff}))(\epsilon_{tel}/(\epsilon_{tel}+\epsilon_{AO}))\right]^{1/2}$$

For an 8m telescope with 0.7” seeing for 2.2 μm observations.

In the natural seeing limit, we have

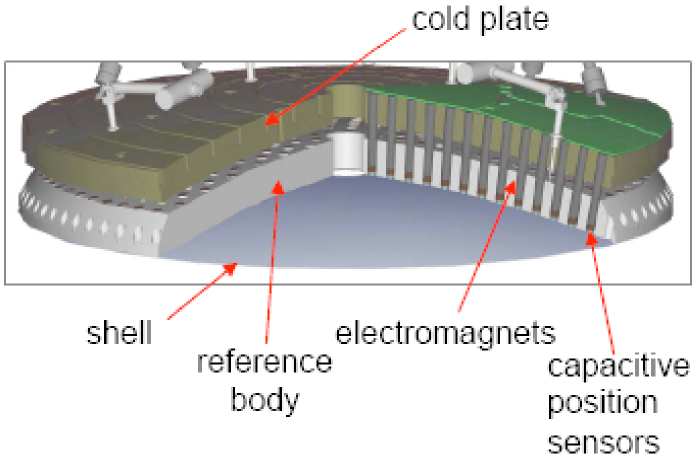
$\eta_{slit} = 0.5$ $\epsilon_{tel}=0.1$

For AO, we have $\theta_{diff}= 0.057$”, m=4 ($2\lambda/D$ slit), $\eta_{strehl}=0.25$, $\epsilon_{AO}= 0.25$

In this situation, the ratio of S/N’s is **1**

You only break even.

How are things going to be different on 30m telescopes?



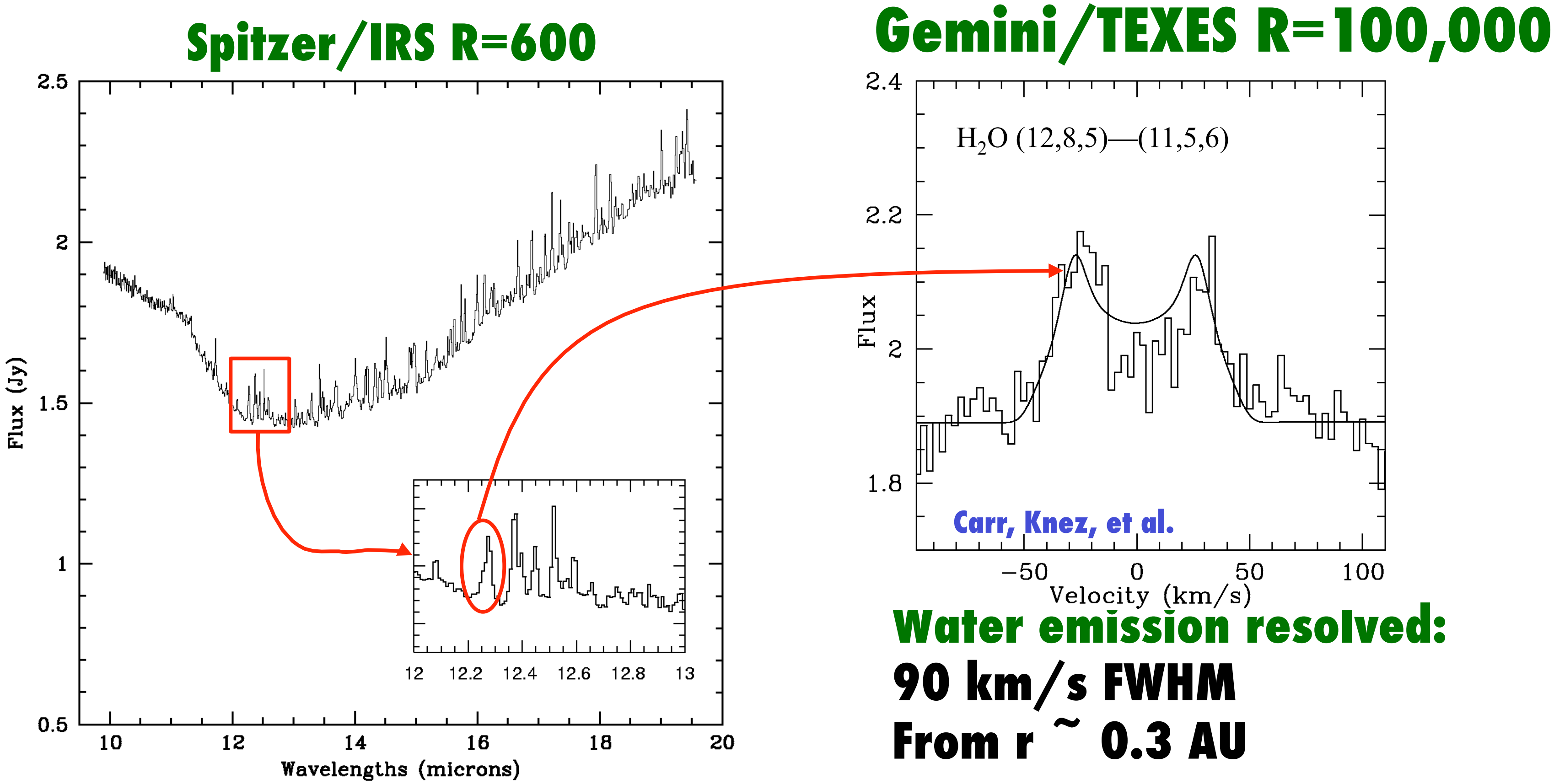
GMT adaptive secondary
(courtesy of P.Hinz).

By using an adaptive secondary and cool relay optics, ε_{AO} can be reduced to ~0.05. The value of $\Omega_{slit}/\Omega_{diff}$ increases by more than an order of magnitude.

<u>Bottom line</u>: An AO system with these parameters can be **20** times more sensitive than a natural seeing instrument.

Not only are we lazy, but we aren't too bright.
The discovery space for high resolution spectroscopy
is in the spectral direction. To avoid thinking too hard,
we need broad spectral coverage.

Knez et al., Carr et al. H_2O emission in T-Tauri Disks



Spitzer/IRS R=600

Gemini/TEXES R=100,000

Water emission resolved:

90 km/s FWHM

From r ~ 0.3 AU

Line profiles, temperatures, and emitting areas indicate origin in planet formation region of disk

Science Common Denominator: Need broad spectral coverage and large resolving power.

Current Instruments:

NIRSPEC: R to 37,000. $\Delta\lambda/\lambda \sim 0.05$ not continuous [1024^2]

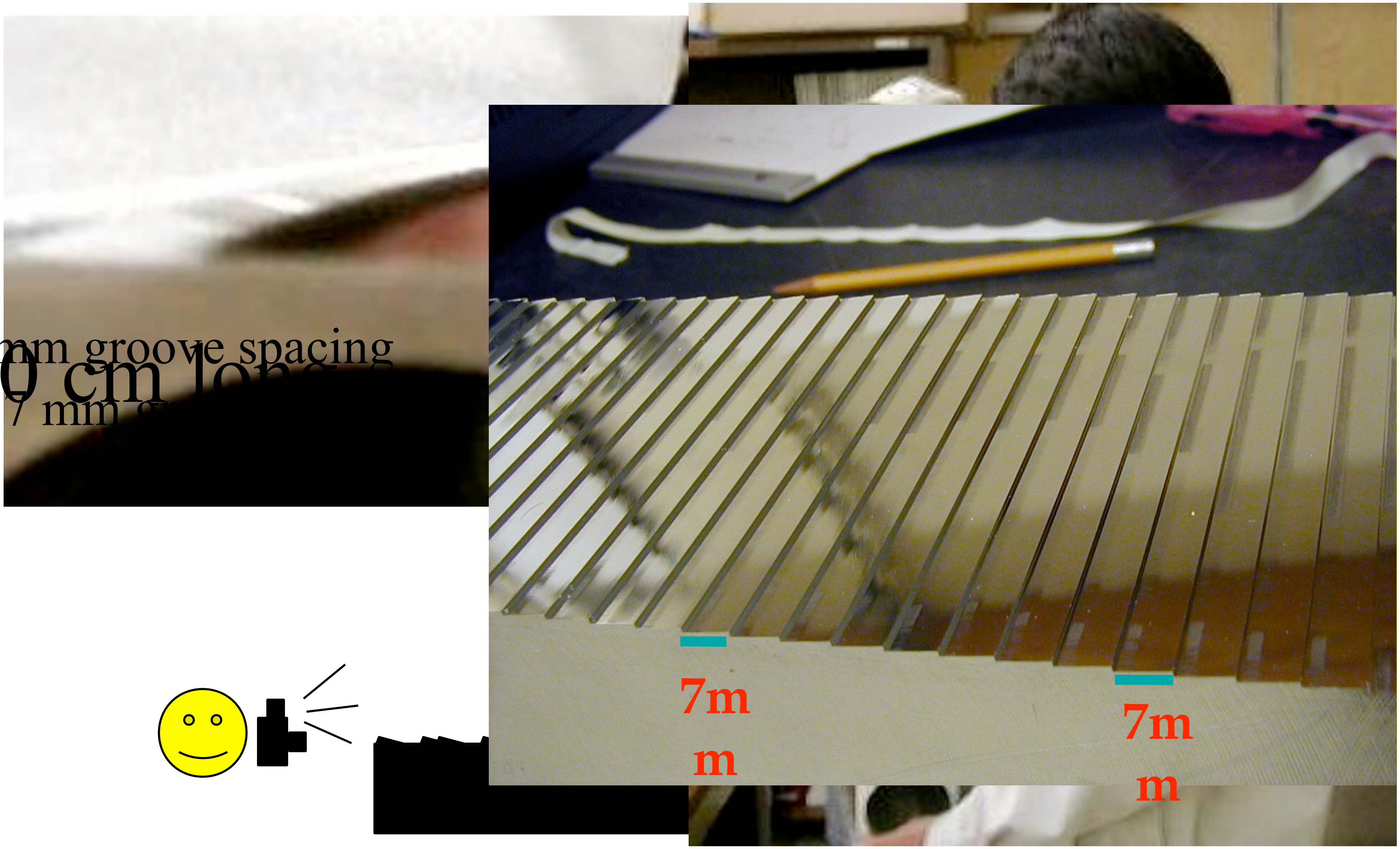
Phoenix: R to 80,000 $\Delta\lambda/\lambda \sim 0.005$ [1024^2]

CRIRES: R to 90,000 $\Delta\lambda/\lambda \sim 0.015$ [$3\text{x}1024^2$]

TEXES: R to 100,000 $\Delta\lambda/\lambda \sim 0.005$ [256^2]

Coarse gratings make significant improvement possible

Echelon Grating



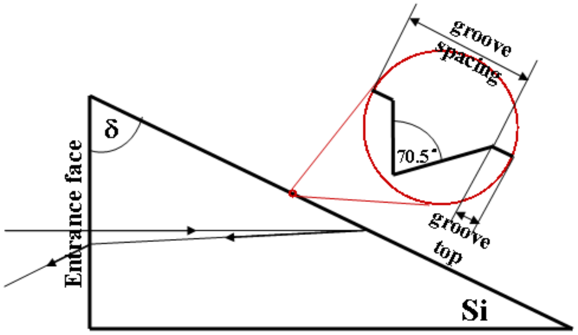
7mm groove spacing

90 cm long

0.7 mm gr

Immersion gratings are the key to a new generation of near-IR spectrographs.

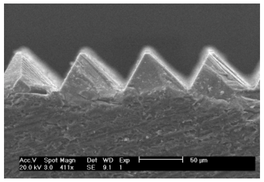
An immersion grating is a grating in which grooves are immersed in a medium with an index of refraction *n*. They provide both high spectral resolution and continuous spectral coverage.



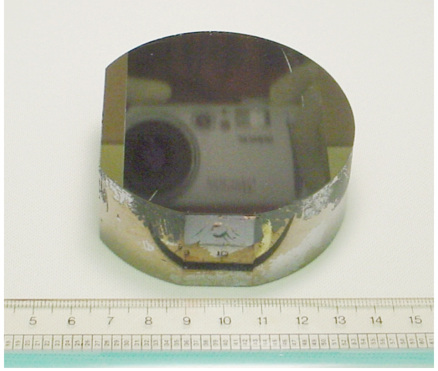
$$m\lambda = n_G \sigma (\sin\alpha + \sin\beta)$$

$$R_{max} = \frac{2 n_G L \sin\delta}{\lambda}$$

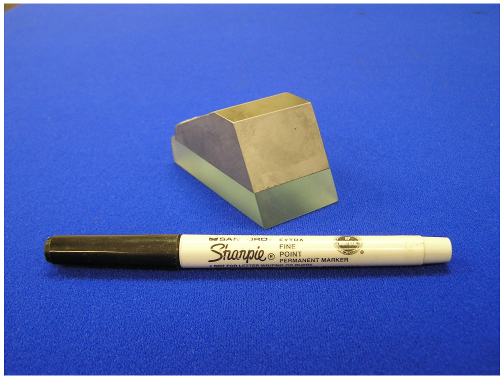
$$\frac{d\beta}{d\lambda} = \frac{2 n_G \tan\beta}{\lambda}$$



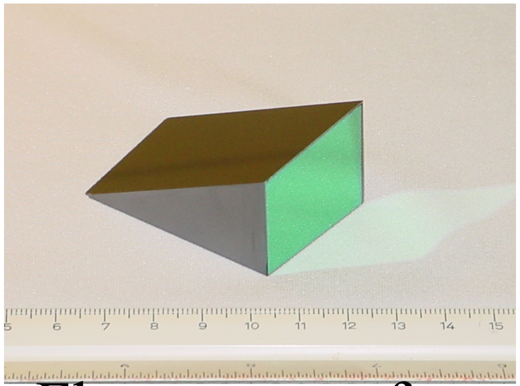
Si Immersion Grating Production



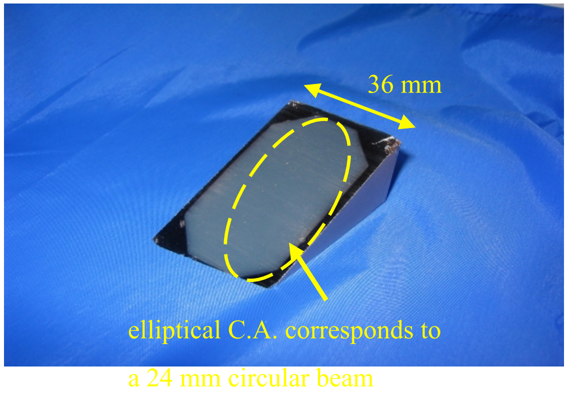
Grating etched into silicon puck



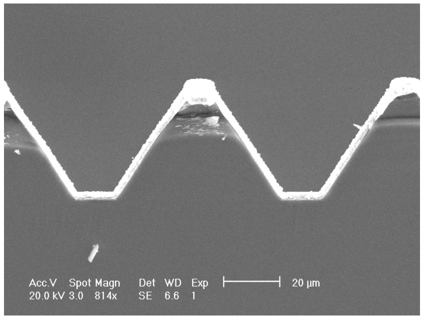
Puck cut into prism and then polished



Flat entrance face antireflection coated

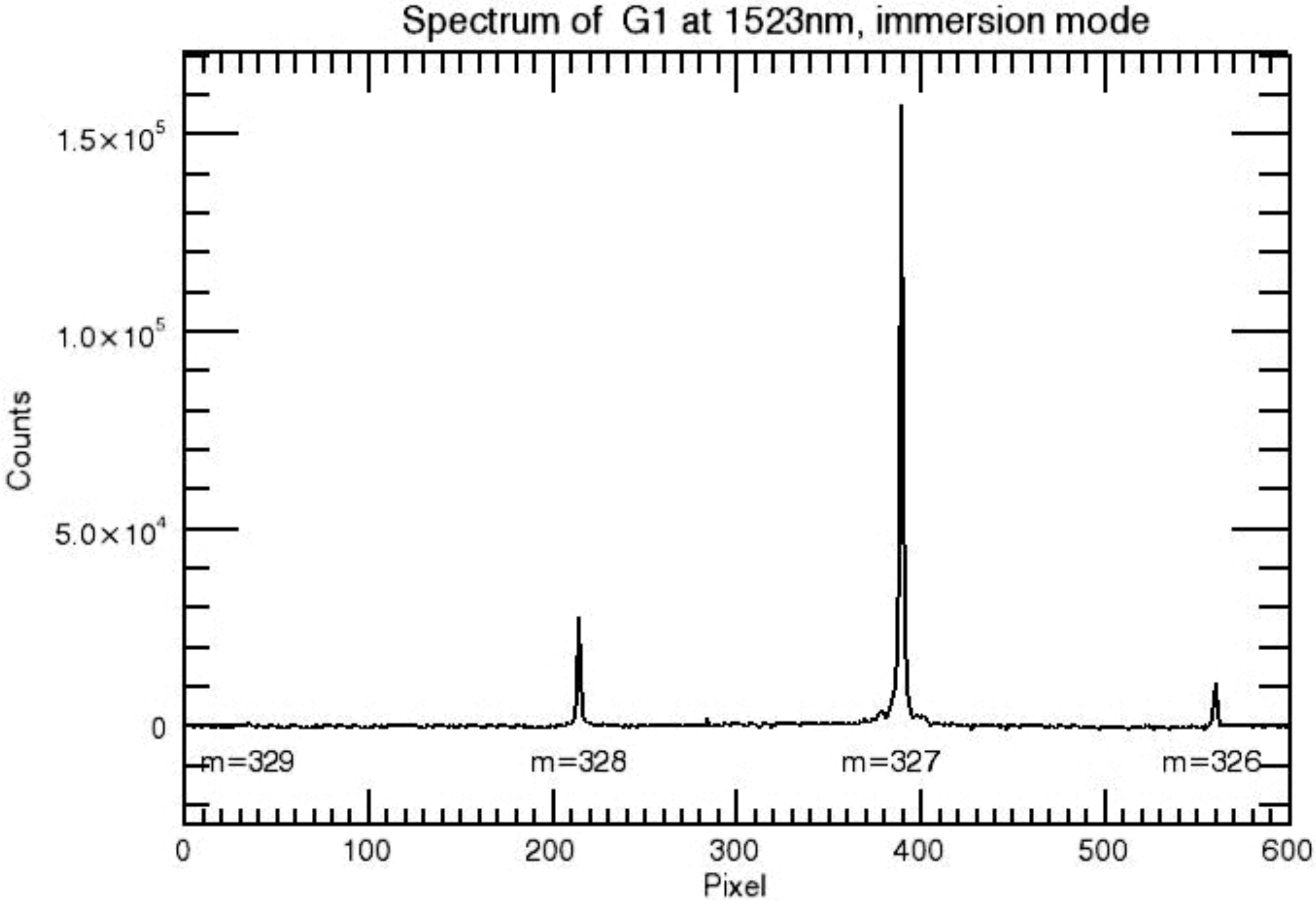


Device completed by aluminizing the grooves along the hypotenuse

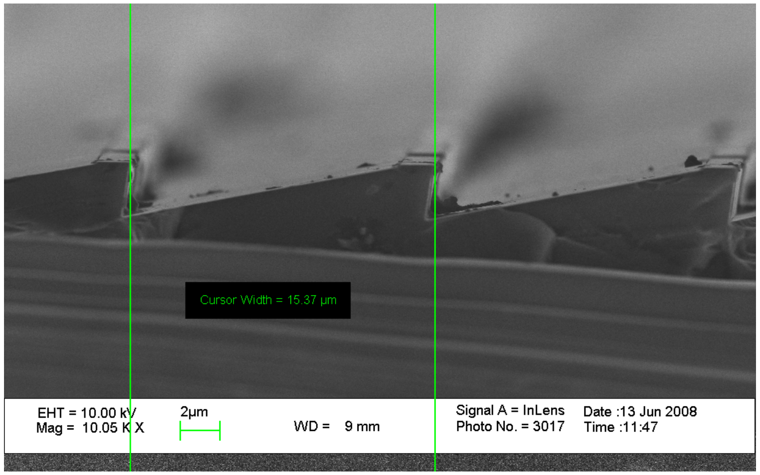


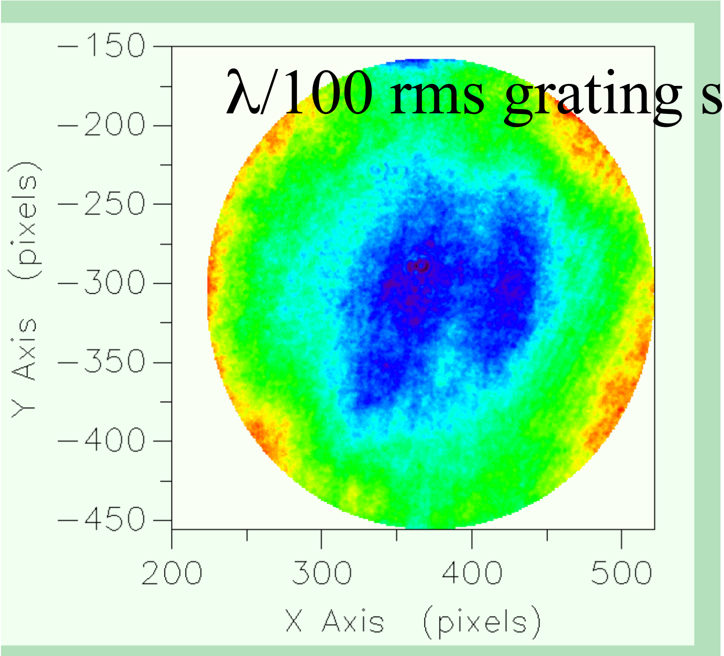
Note: Only the bottom of the coating matters

performance in immersion

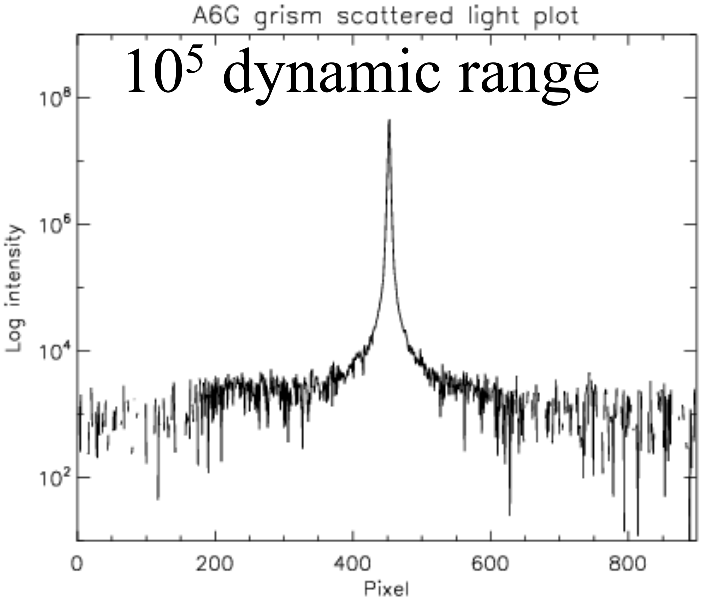


JWST NIRCam Grisms



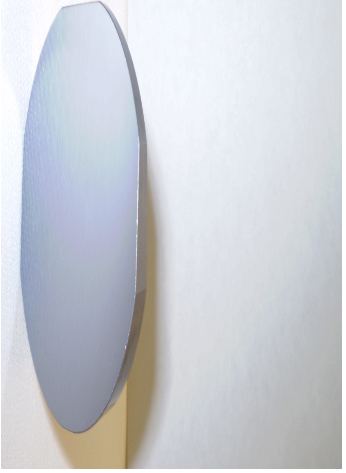


λ/100 rms grating surface

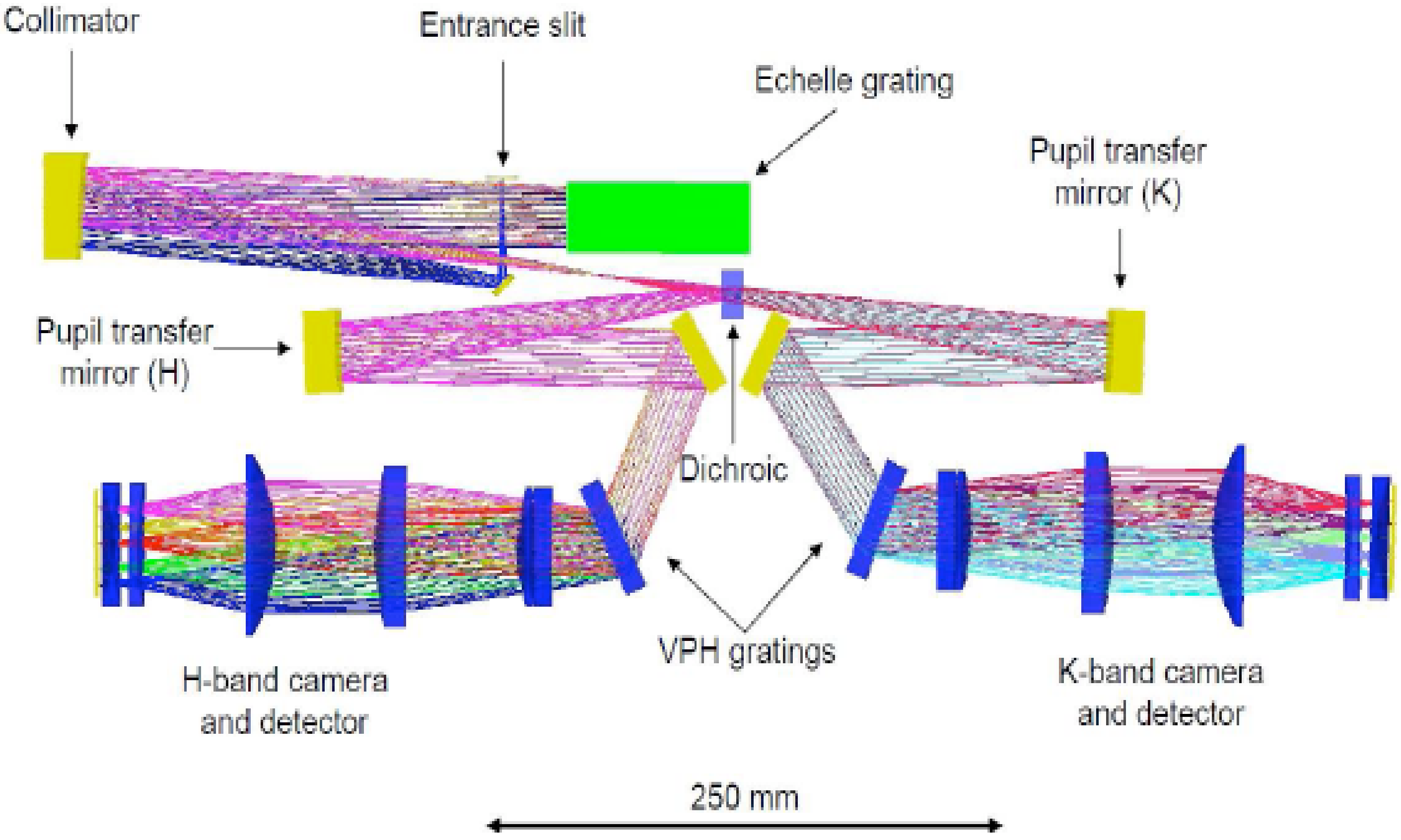


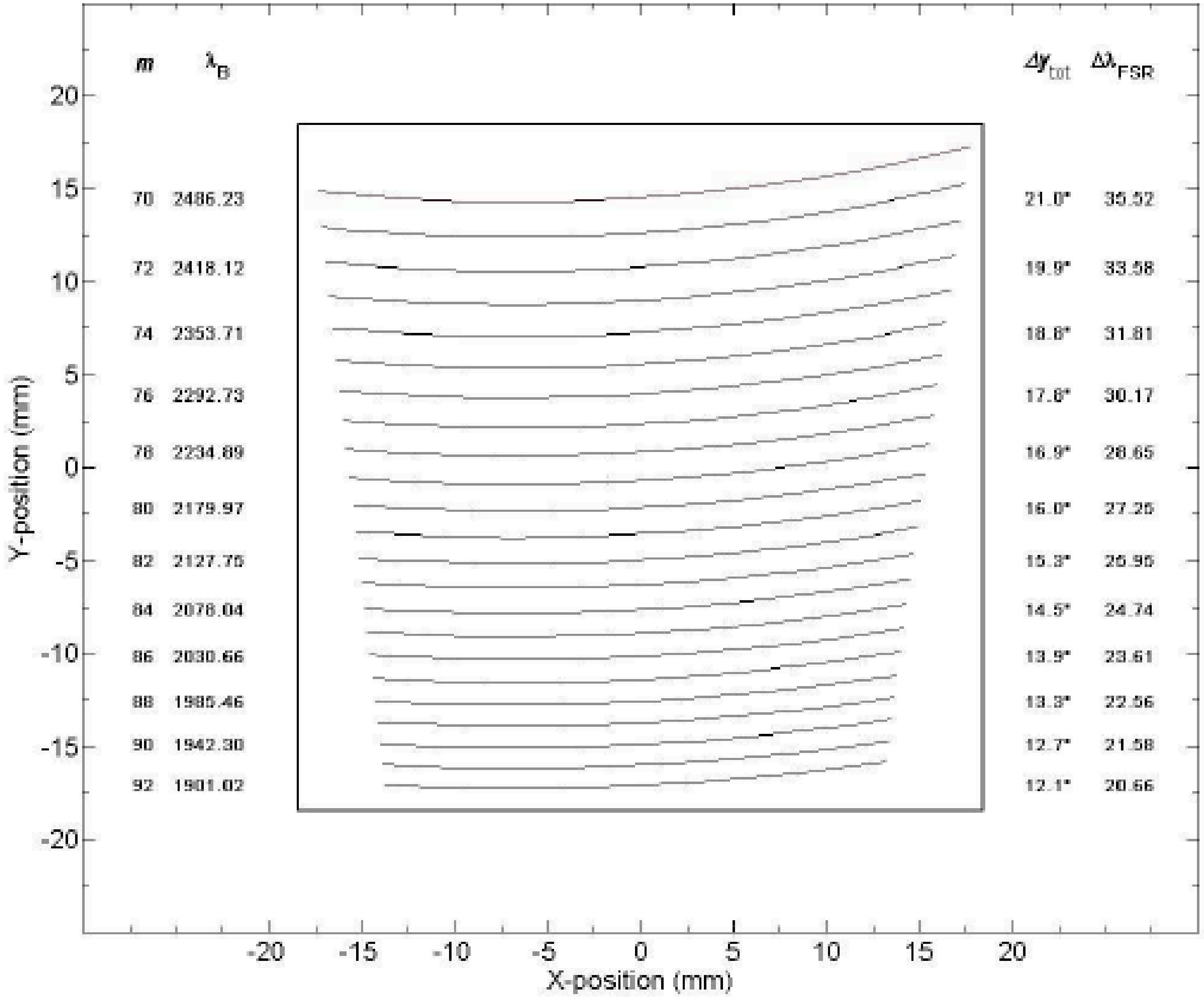
10^5 dynamic range

Flight Part



Instruments in the pipeline:
IGRINS





m
λB
70 2486.23
72 2418.12
74 2353.71
76 2292.73
78 2234.89
80 2179.97
82 2127.76
84 2078.04
86 2030.66
88 1985.46
90 1942.30
92 1901.02
Δytot
ΔλFSR
21.0" 35.52
19.9" 33.58
18.8" 31.81
17.8" 30.17
16.9" 28.65
16.0" 27.25
15.3" 25.95
14.5" 24.74
13.9" 23.61
13.3" 22.56
12.7" 21.58
12.1" 20.66
Y-position (mm)
20
15
10
5
0
-5
-10
-15
-20
X-position (mm)
-20
-15
-10
-5
0
5
10
15
20

Where do we go from here?

-With 4096^2 detectors, we can cover whole windows at R=100,000 with decent slits. This enables instruments with no moving parts.

- Push machined gratings into the near-IR

- Make better and bigger immersion gratings.

High Resolution spectroscopy on ELTs

Can still improve at D^2 or better in sensitivity

Can have vastly better spectral coverage

Combination leads to enormous impact

Sociology and Astronomical Instrumentation:

1)Inflation of expectations in performance and service
Ground based spectrographs at national facilities went
from 300K (1978 dollars) to 30 M (2005 dollars)

2)The killer app vs. the kitchen sink
Are we looking for the God particle or providing a
capability for every possible purpose in one instrument?

How we can break the barrier?
Keep Teams small, 100% time, one institution
Team knows science
Keep building

Oversight but not overkill- extension service.
Keep designs simple- push back on operations people
Make device development and instrumentation part
of the culture

My own experience:
Fazio- Hildebrand- Townes/Genzel groups

Experimental Physicist, strong and lasting interest in astronomical problems.

Need to keep training and valuing people with these traits.

Giovanni is proud of taping his own PMTs for space missions- believe it or not, you can still do stuff like that.

Thank you