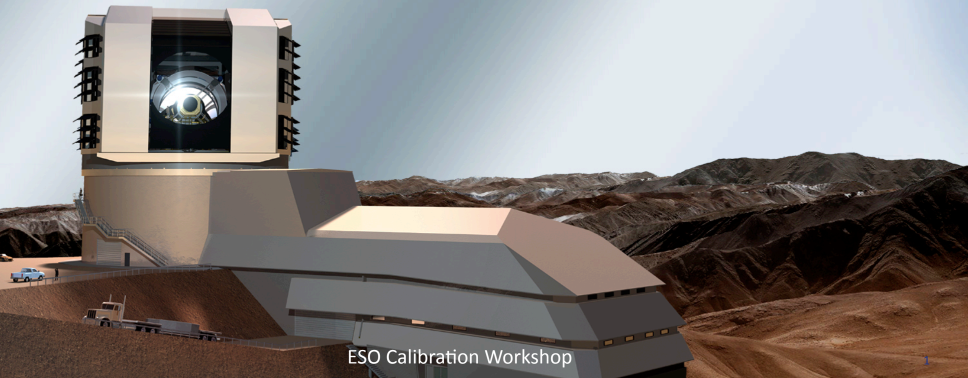
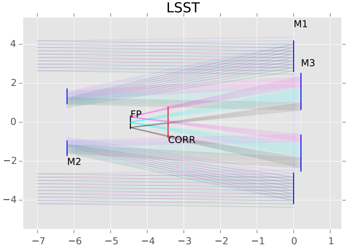
Robert Lupton
LSST Pipeline and Calibration Scientist (pro tem)

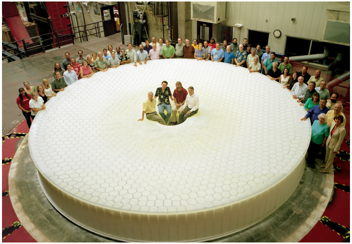
LSST's Calibration Strategy

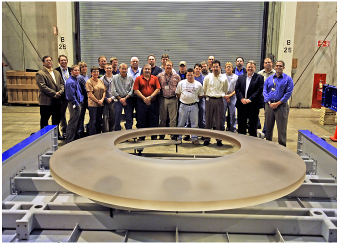
2017-01-19



The Large Synoptic Survey Telescope's Optics

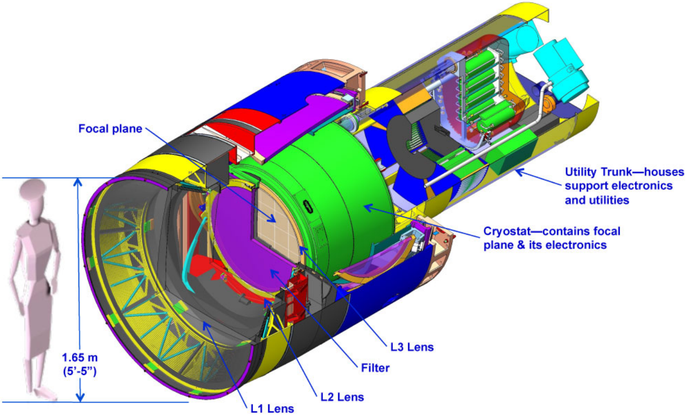






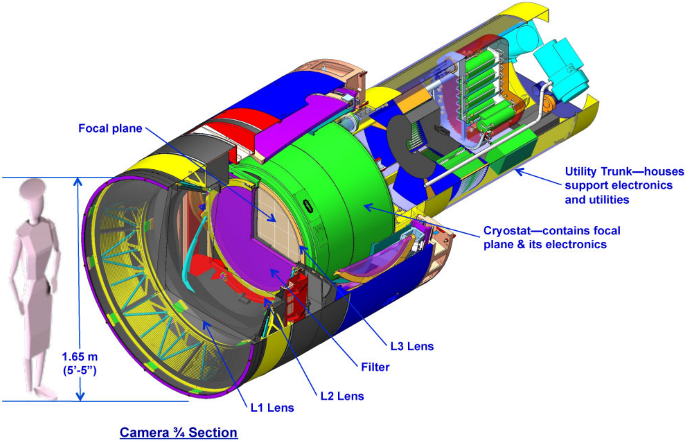
Three mirrors: an 8.4m primary, a 3.4m secondary, and a 5m tertiary.

The Large Synoptic Survey Telescope's Camera



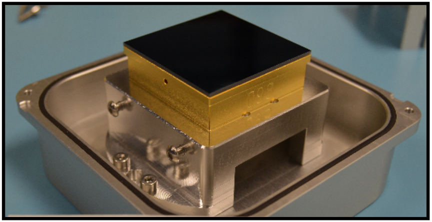
Camera ¾ Section

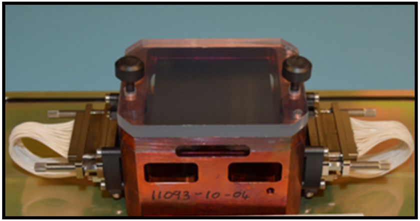
The Large Synoptic Survey Telescope's Camera

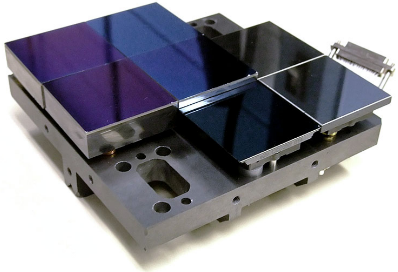


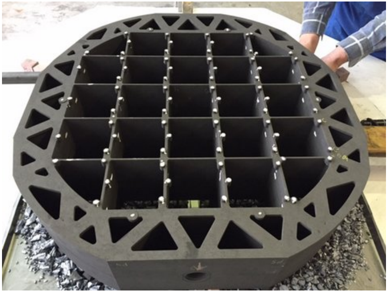
16 amplifiers × 520 kHz readout (2s); 3.2 GPixels every 18s; *c.* 400 MB/s
20 TB/night; 60 PB over 10 years for raw data and 15 PB for the catalog database.

CCDs and Rafts

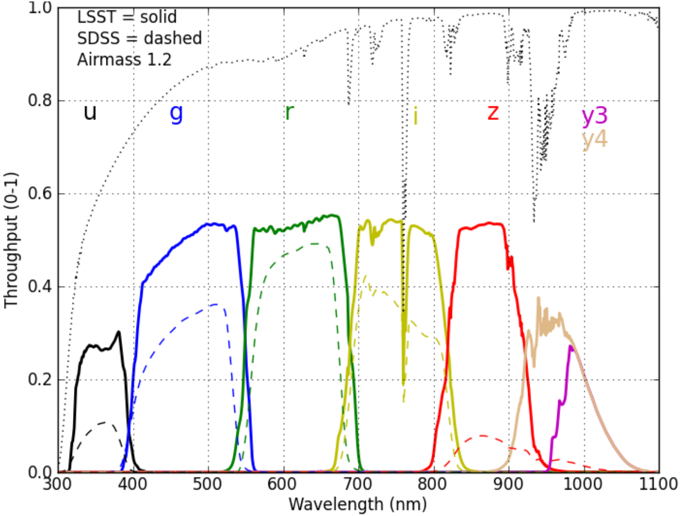








Filter Complement



76cm diameter; meniscus substrate.

The Calibration Problem

We measure:

$$C_{raw,b} = \frac{\pi D^2 \Delta t}{4gh} \int_0^\infty F_\nu S^{atm} S_b^{sys} \, d\lambda/\lambda$$

The Calibration Problem

We measure:

$$C_{raw,b} = \frac{\pi D^2 \Delta t}{4gh} \int_0^\infty F_\nu S^{atm} S_b^{sys} \, d\lambda/\lambda$$

but we want to know

$$C_{std,b} \equiv \int_0^\infty F_\nu S_{b,std} \, d\lambda/\lambda$$

given $C_{raw,b}$

The Calibration Problem

We measure:

$$C_{raw,b} = \frac{\pi D^2 \Delta t}{4gh} \int_0^\infty F_\nu S^{atm} S_b^{sys} \, d\lambda/\lambda$$

but we want to know

$$C_{std,b} \equiv \int_0^\infty F_\nu S_{b,std} \, d\lambda/\lambda$$

given $C_{raw,b}$

We also need to calibrate the astrometry, but that problem's been made trivial by Gaia.

$C_{std,b}$

We need:

- $C_{raw,b}$
- the detector sensitivity $S_b^{sys}(\lambda, \boldsymbol{x})$, including
  - the atmospheric transmissivity $S^{atm}(\lambda)$
  - the telescope (including optics and filters)
  - the detector efficiencies
- the object's SED

LSST's Calibration Datasets

Measuring $S_b^{sys}(\lambda, \boldsymbol{x})$ requires us to measure the variation with

- $\boldsymbol{x}$ (the flatfield)
- λ (the effective filter bandpass)

LSST's Calibration Datasets

Measuring $S_b^{sys}(\lambda, \boldsymbol{x})$ requires us to measure the variation with

- $\boldsymbol{x}$ (the flatfield)
- λ (the effective filter bandpass)

We can measure:

- Broad-band flats

LSST's Calibration Datasets

Measuring $S_b^{sys}(\lambda, \boldsymbol{x})$ requires us to measure the variation with

- $\boldsymbol{x}$ (the flatfield)
- λ (the effective filter bandpass)

We can measure:

- Broad-band flats
- "Monochromatic" (*c.* 1nm bandwidth) flats

LSST's Calibration Datasets

Measuring $S_b^{sys}(\lambda, \boldsymbol{x})$ requires us to measure the variation with

- $\boldsymbol{x}$ (the flatfield)
- λ (the effective filter bandpass)

We can measure:

- Broad-band flats
- "Monochromatic" (*c.* 1nm bandwidth) flats
- Dithered star fields

LSST's Calibration Datasets

Measuring $S_b^{sys}(\lambda, \boldsymbol{x})$ requires us to measure the variation with

- $\boldsymbol{x}$ (the flatfield)
- λ (the effective filter bandpass)

We can measure:

- Broad-band flats
- "Monochromatic" (*c.* 1nm bandwidth) flats
- Dithered star fields
- A collimated "monochromatic" projector calibrated with NIST photodiodes

LSST's Calibration Datasets

Measuring $S_b^{sys}(\lambda, \boldsymbol{x})$ requires us to measure the variation with

- $\boldsymbol{x}$ (the flatfield)
- λ (the effective filter bandpass)

We can measure:

- Broad-band flats
- "Monochromatic" (*c.* 1nm bandwidth) flats
- Dithered star fields
- A collimated "monochromatic" projector calibrated with NIST photodiodes

And for $S^{atm}(\lambda)$

- A 1.2m telescope with R $\sim$ 300 --- 400 spectrophotometry

The instrumental sensitivity S_b^{sys}

A flatfield image doesn't give S_b^{sys} directly due to:

- scattered light
- ghosting
- vignetting (if the screen isn't perfect; which it isn't)

The instrumental sensitivity S_b^{sys}

A flatfield image doesn't give S_b^{sys} directly due to:

- scattered light
- ghosting
- vignetting (if the screen isn't perfect; which it isn't)

it also includes pixel-size variations

The instrumental sensitivity S_b^{sys}

A flatfield image doesn't give S_b^{sys} directly due to:

- scattered light
- ghosting
- vignetting (if the screen isn't perfect; which it isn't)

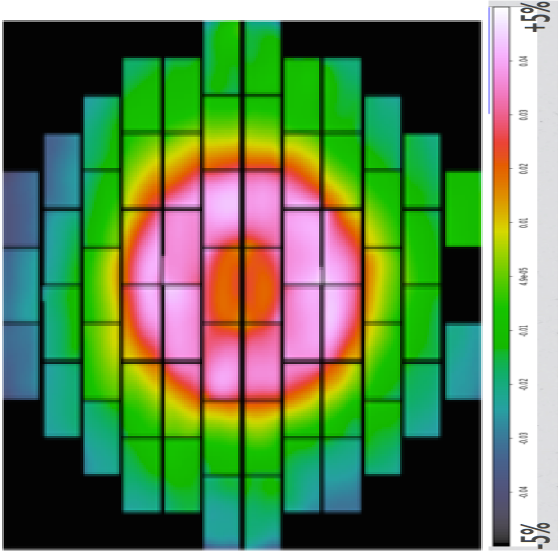
it also includes pixel-size variations

The classic solution is to:

- Assume that the dome flat gives the pixel-to-pixel variability
- Use dithered star fields to correct the dome flat for scattered light masquerading as sensitivity variation

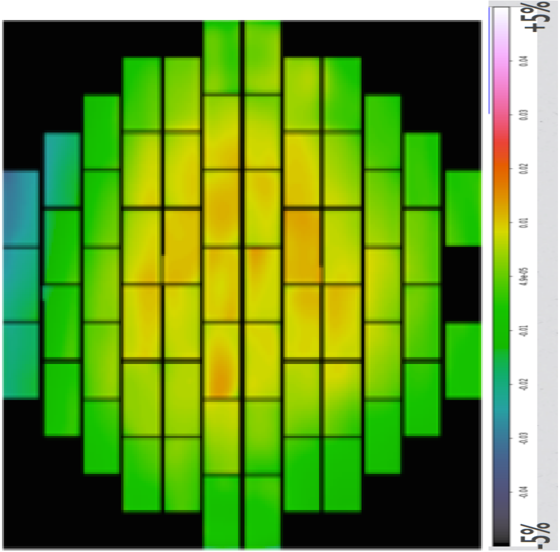
DES Starflats

g



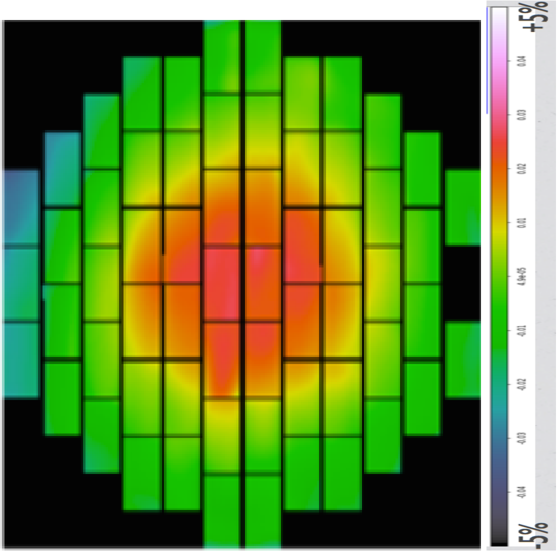
DES Starflats

r



DES Starflats

i



Monochromatic Starflats

LSST is interested in the effects of the object's SED on their photometry, so we'd need to repeat this analysis including the stars' colours.

Monochromatic Starflats

LSST is interested in the effects of the object's SED on their photometry, so we'd need to repeat this analysis including the stars' colours.
We'd also need to monitor the filters, so we'd like to understand monochromatic flats.

Monochromatic Starflats

LSST is interested in the effects of the object's SED on their photometry, so we'd need to repeat this analysis including the stars' colours.

We'd also need to monitor the filters, so we'd like to understand monochromatic flats.

We plan to use star flats as a cross-check, not a primary measurement.

Monochromatic Starflats

LSST is interested in the effects of the object's SED on their photometry, so we'd need to repeat this analysis including the stars' colours.
We'd also need to monitor the filters, so we'd like to understand monochromatic flats.
We plan to use star flats as a cross-check, not a primary measurement.

Alternatively, if we could only find a field full of monochromatic point-sources …

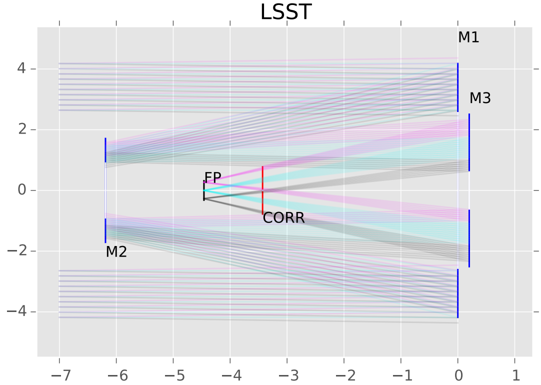
The Collimated Projector

LSST will have a monochromatic projector with an image mask.

The Collimated Projector

LSST will have a monochromatic projector with an image mask.

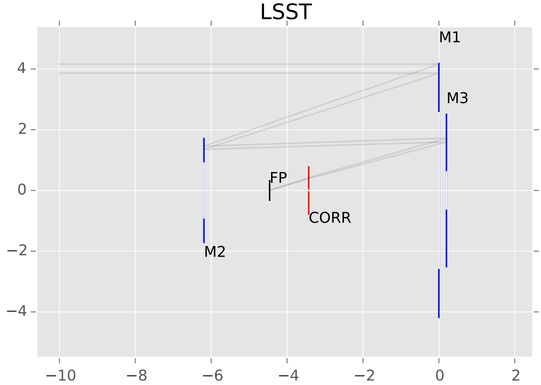
With a 30cm diameter projector the beam has a divergence of *c.* 1/3 arcsec, which is then imaged into a 1/3 arcsec spot by the LSST optics.



The Collimated Projector

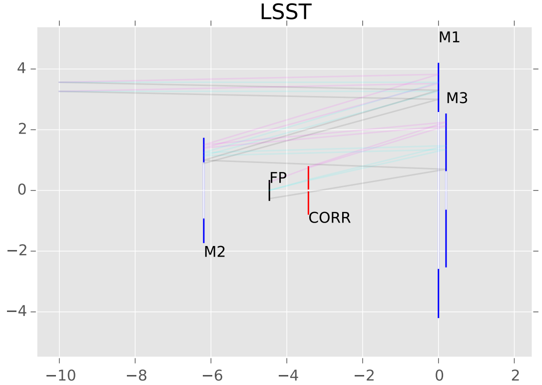
LSST will have a monochromatic projector with an image mask.

With a 30cm diameter projector the beam has a divergence of *c.* 1/3 arcsec, which is then imaged into a 1/3 arcsec spot by the LSST optics.



The Collimated Projector

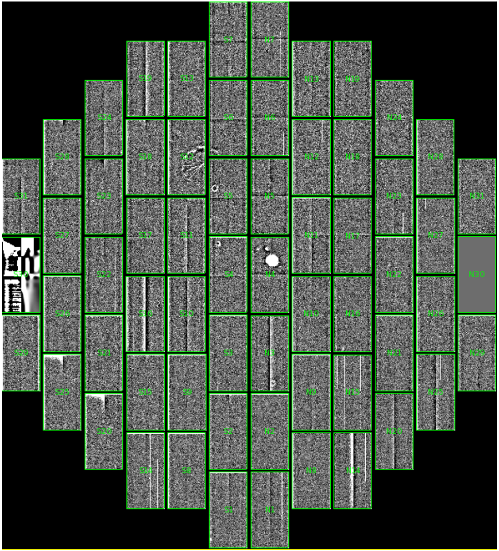
LSST will have a monochromatic projector with an image mask.
With a 30cm diameter projector the beam has a divergence of *c.* 1/3 arcsec, which is then imaged into a 1/3 arcsec spot by the LSST optics.



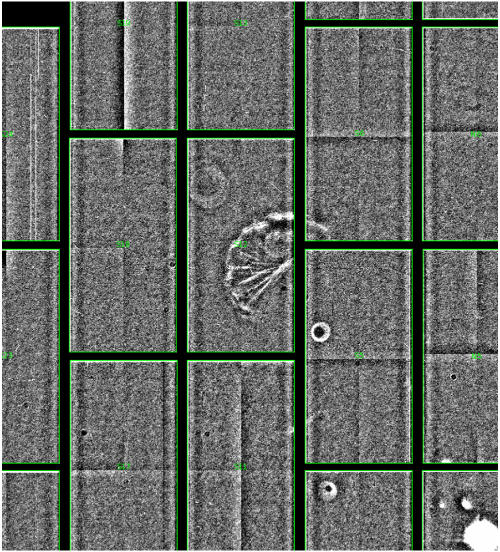
We can project many spots simultaneously.

The CBP at the Blanco

The CBP at the Blanco



The CBP at the Blanco



"Star" Flats

We've measured the relative response of a set of points on all the CCDs in the focal plane at a fixed λ.

"Star" Flats

We've measured the relative response of a set of points on all the CCDs in the focal plane at a fixed λ. The monochromatic dome flat taken at the same λ gives the pixel-to-pixel variation; we need to merge these two pieces of information to achieve a monochromatic flat.

"Star" Flats

We've measured the relative response of a set of points on all the CCDs in the focal plane at a fixed λ. The monochromatic dome flat taken at the same λ gives the pixel-to-pixel variation; we need to merge these two pieces of information to achieve a monochromatic flat.

If we then scan in λ, you get the sensitivity curve for each spot

Monochromatic Flats

For many cameras the spatial structure of the ghosts has sharp features, which makes the construction of flat fields from spot sensitivities tricky. Furthermore, we need *c.* $(6.7/0.30)^2 == 500$ exposures per wavelength and we have to repeat for every *c.* 1nm step in wavelength for each filter.

Monochromatic Flats

For many cameras the spatial structure of the ghosts has sharp features, which makes the construction of flat fields from spot sensitivities tricky. Furthermore, we need *c.* $(6.7/0.30)^2 == 500$ exposures per wavelength and we have to repeat for every *c.* 1nm step in wavelength for each filter. This is expensive.

Monochromatic Flats

For many cameras the spatial structure of the ghosts has sharp features, which makes the construction of flat fields from spot sensitivities tricky. Furthermore, we need *c.* $(6.7/0.30)^2 == 500$ exposures per wavelength and we have to repeat for every *c.* 1nm step in wavelength for each filter. This is expensive.

If we know the filter bandpasses $\mathcal{S}_b^{filt}(\boldsymbol{i})$ at every point in the focal plane we may use a slightly different approach.

Using Unfiltered Spots

If we take both domeflat and collimated projector data without a filter in the beam we may repeat the above analysis without the $\mathcal{S}_b^{filt}$.

Using Unfiltered Spots

If we take both domeflat and collimated projector data without a filter in the beam we may repeat the above analysis without the $\mathcal{S}_b^{filt}$.
This has two advantages:

- there are no strongly chromatic elements so we can use larger steps in wavelength
- the ghost image should be much weaker

Using Unfiltered Spots

If we take both domeflat and collimated projector data without a filter in the beam we may repeat the above analysis without the $\mathcal{S}_b^{filt}$.

This has two advantages:

- there are no strongly chromatic elements so we can use larger steps in wavelength
- the ghost image should be much weaker

It's now plausible that we really can estimate the per-pixel monochromatic flat:

- We know $\mathcal{S}^{!filt}(\lambda)$ from the no-filter flats and spots.
- We know $\mathcal{S}_b^{filt}(\lambda, \boldsymbol{i})$ from vendor measurements.

Using Unfiltered Spots

If we take both domeflat and collimated projector data without a filter in the beam we may repeat the above analysis without the $\mathcal{S}_b^{filt}$.
This has two advantages:

- there are no strongly chromatic elements so we can use larger steps in wavelength
- the ghost image should be much weaker

It's now plausible that we really can estimate the per-pixel monochromatic flat:

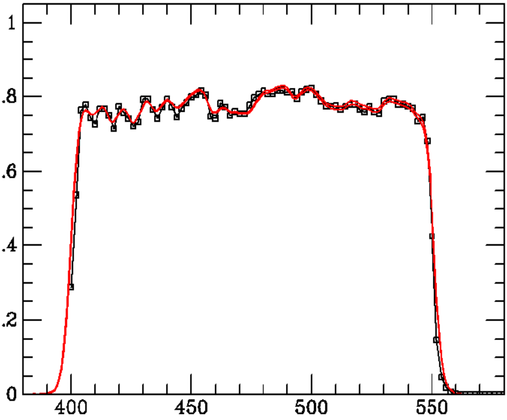
- We know $\mathcal{S}^{!filt}(\lambda)$ from the no-filter flats and spots.
- We know $\mathcal{S}_b^{filt}(\lambda, \boldsymbol{i})$ from vendor measurements. Which I may or may not believe to be correct and relevant

Filter Response Curve

By scanning in λ with and without a filter we may measure $\mathcal{S}_b^{filt}(\lambda)$

Filter Response Curve

By scanning in λ with and without a filter we may measure $\mathcal{S}_b^{filt}(\lambda)$



vendor data tunable laser in dome (Stubbs and Tonry, PanSTARRS)

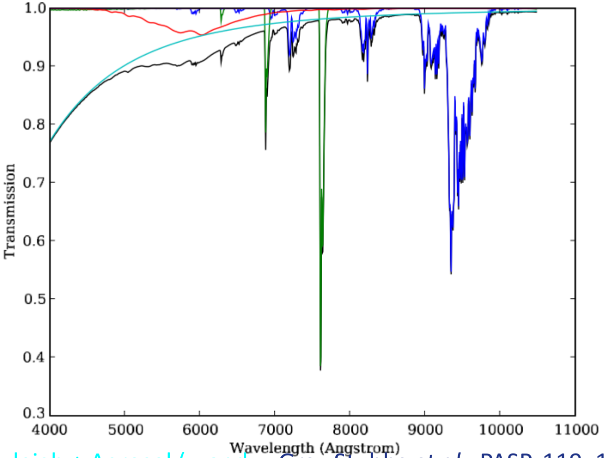
The atmospheric transmissivity $S^{atm}(\lambda)$

What about the atmosphere?

Unfortunately the atmosphere is between the telescope and the rest of the Universe.

What about the atmosphere?

Unfortunately the atmosphere is between the telescope and the rest of the Universe.



O_2 O_3 H_2O Rayleigh + Aerosol (τ and α Gray Stubbs *et al.*, PASP, 119, 1163, (2007)

Burke *et al.*, ApJ 720, 811B (2010)

The corresponding absorption spectra may be calculated using MODTRANS or equivalent

Monitor Telescope

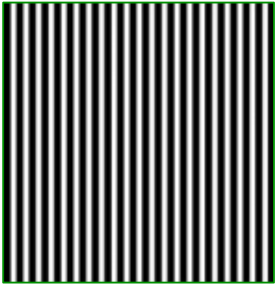
We will have a 1.2m "auxiliary" telescope on Cerro Pachon, equipped with a spectrograph.

Monitor Telescope

We will have a 1.2m "auxiliary" telescope on Cerro Pachon, equipped with a spectrograph.

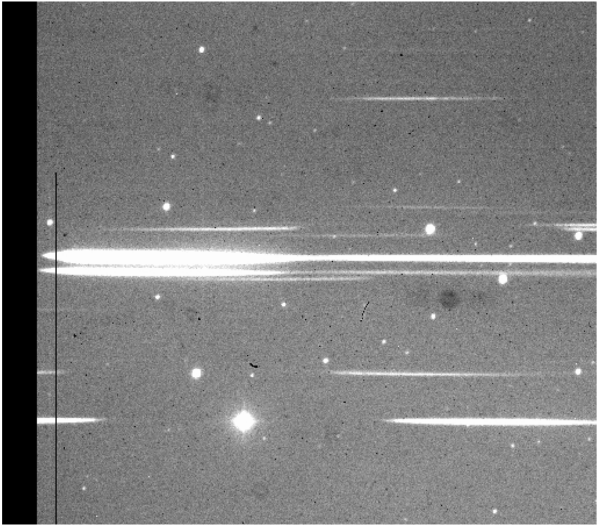
The current plan is to almost-always observe a bright star (8-10) in the 10 $\deg^2$ field of the 8.4m.

Proposed Hardware: A Ronchi Grating



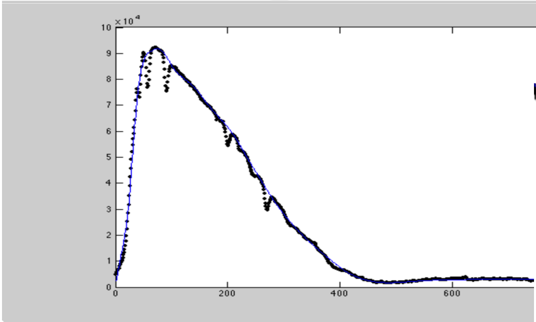
- 50-50 transmission pattern on glass
- Flat spectral response
- Even order light highly suppressed by zeros in single-slit diffraction pattern
- 20% of incident light goes in to $m=\pm1$ order
- 25% of incident light goes into $m=0$ order

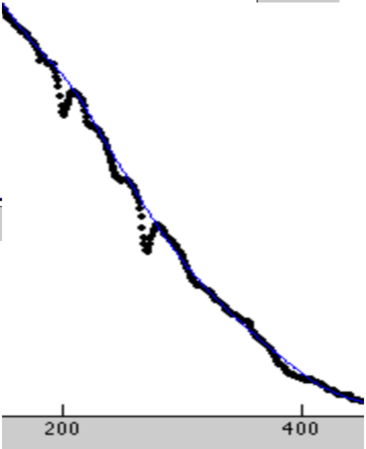
Slitless dispersed image from CTIO 0.9m



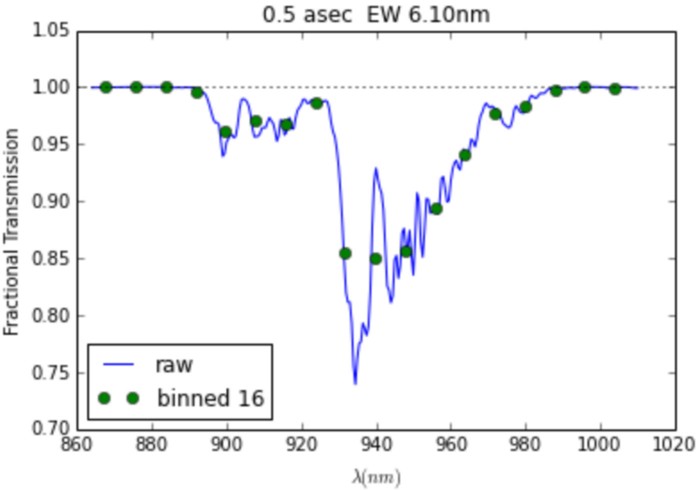
200 lines/mm grating

Slitless dispersed image from CTIO 0.9m

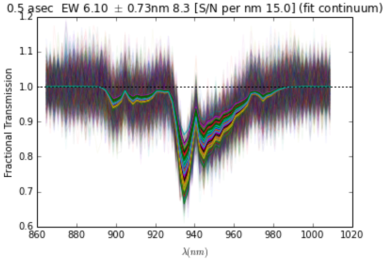


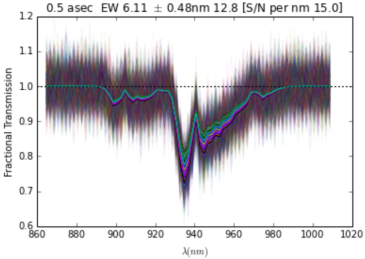


Water Vapour Modtrans

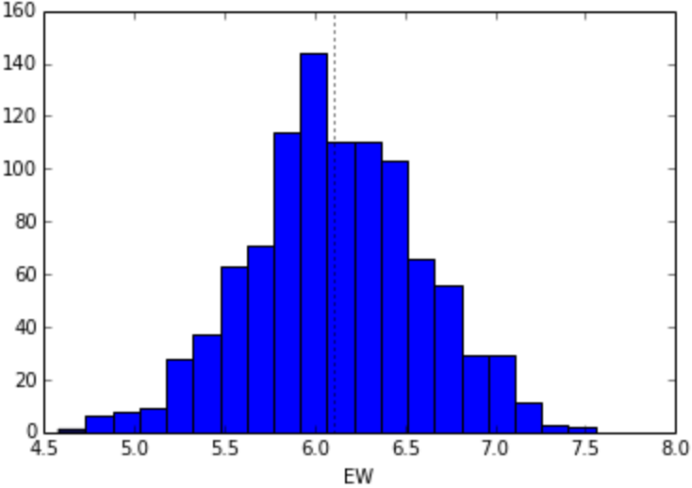


Water Vapour Fitting

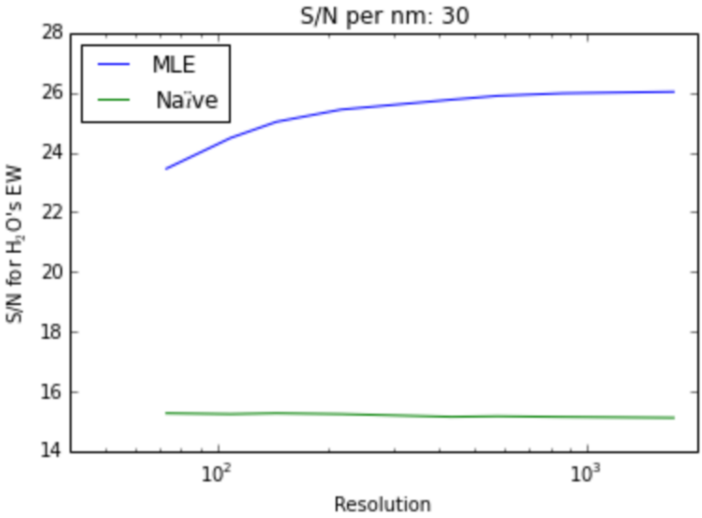




Water Vapour Fitting



Water Vapour Signal-to-Noise

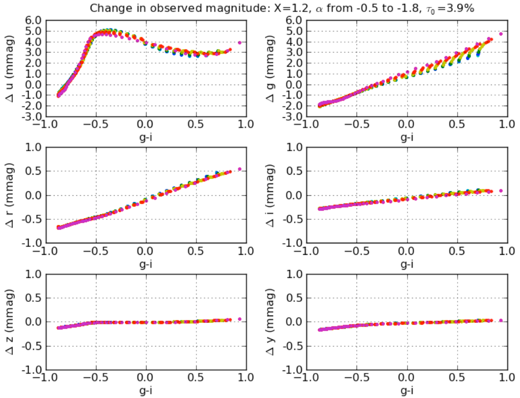


Using Sets of Stars

We will have many-colour photometry (*ugrizy*) of many, many stars in each of many many visits.

Using Sets of Stars

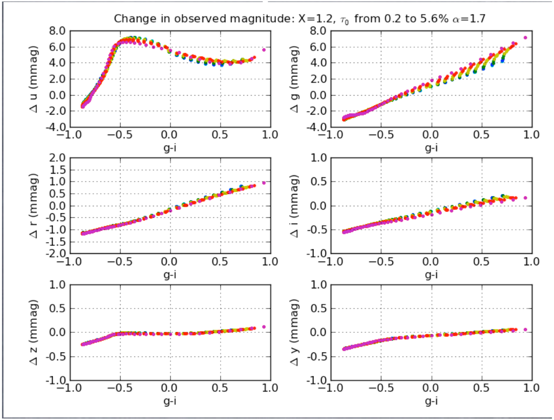
We will have many-colour photometry (*ugrizy*) of many, many stars in each of many many visits.



Aerosols α

Using Sets of Stars

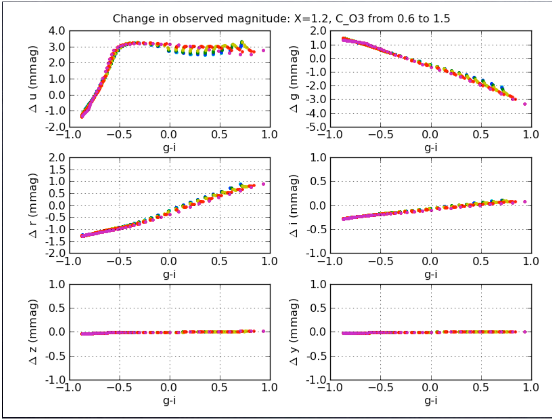
We will have many-colour photometry (*ugrizy*) of many, many stars in each of many many visits.



Aerosols τ_0

Using Sets of Stars

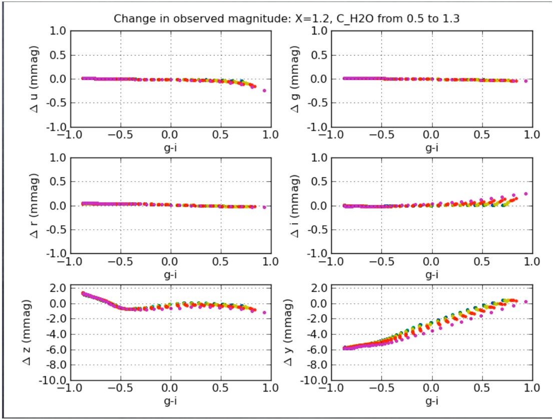
We will have many-colour photometry (*ugrizy*) of many, many stars in each of many many visits.



O_3

Using Sets of Stars

We will have many-colour photometry (*ugrizy*) of many, many stars in each of many many visits.



H_2O

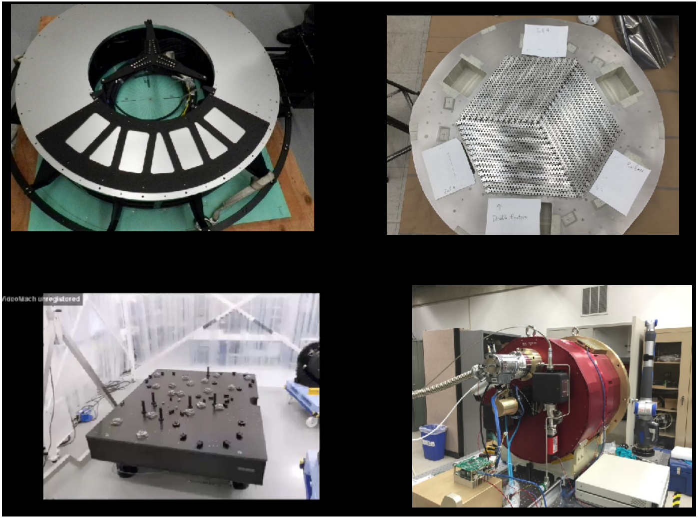
Using Sets of Stars

We will have many-colour photometry (*ugrizy*) of many, many stars in each of many many visits.

Even if the photometry is unable to constrain S^{atm} well enough to satisfy the SRD requirements, we will be able to analyse wide-field camera data to explore the structure functions.

The End

Subaru's Prime Focus Spectrograph (PFS)



1.3 square degree field   2396 fibres   380-1260nm   first light 2019

The End