Photometric Calibration: Precision Measurement of Atmospheric Extinction

David L. Burke
KIPAC/SLAC

for the LSST Calibration Team

T. Axelrod, J. Bartlett, S. Blondin, D. Burke, D. Cinabro, C. Claver, M. Creze, J. Frank, J. Haggerty, Z. Ivezic, L. Jones, B. Meadows, D. Monet, P. O'Connor, B. Popescu, A. Saha, A. Smith, C. Smith, C. Stubbs

DES Calibration Workshop
Fermilab July 13, 2008

Photometric SRD Specifications

- Repeatability of measured flux over epochs 0.005 mag (rms)
- Internal zero-point uniformity for all stars across the sky 0.010 mag (rms) in *g,r,i,z* ; 0.020 in other bands
- Transformations between internal photometric bands known to 0.005 mag (rms) in *g,r,i,z*; 0.010 to other bands
- Transformation to a physical scale with accuracy of 0.020 mag

LSST specifications are "factor of two" tighter than typically achieved.

E. g. SDSS Sky Server catalogs internal relative calibrations to ~ 2%.

Ivezic, et al. (2004).

SDSS Stripe 82 and Übercal

Padmanabhan, Schlegel, Finkbeiner, et al. (2007).

Multiple epochs (30-40)

Main sequence stars (~ 10^7) as internal relative calibrators

Photometric Model

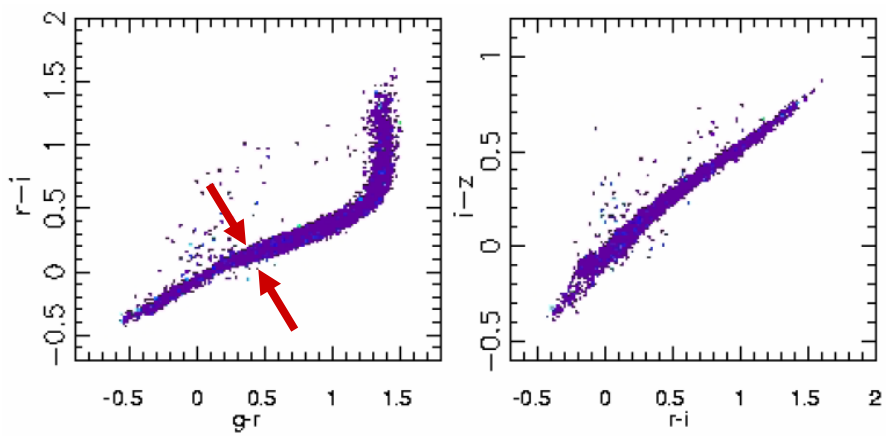
$$m = m_{ADU} + a_\alpha + f_\gamma(j) - \left[k_\beta + \left(\frac{dk}{dt}\right)_\beta (t - t_{\beta,ref})\right] x$$

(airmass)

Observed instrumental magnitude

Instrument response and flat-field

Nightly linear time evolution of extinction
Auxiliary telescope used to measure average dk/dt for entire survey



Uniformity of zero points <u>in photometric conditions</u>:

gri ≤ 5 milli-mags

uz ≤ 10 milli-mags

→ Meets LSST goals

Conclusions from SDSS and Issues for LSST

SDSS is proof-of-principle under ideal conditions

Analysis indicates that variations in atmospheric extinction that are un-observed and un-modeled dominate residual calibration errors

Better control will be required to meet LSST goals over the course of the survey

Issues for LSST

- Non-concurrent broad-band data
- Limited time-on-the-sky for calibration

Photometric Calibration Elements

Accumulated LSST
Multi-Epoch Survey

Science Targets

Reference Stars
($\geq$ 100 per chip per image)

Photometric Standards
(~ 1 per image)

All Sky Reconstruction
(Data Release)

Auxiliary Data

Atmospheric Extinction
$Z(az,el,\nu,t)$

Instrumental Calibration
$I(x,y,\nu,t)$

CDR Baseline Auxiliary Telescope

1.5m Auxiliary Telescope

Measure atmospheric transmission fast enough and with sufficient resolution to accurately determine extinction Z(az,el,ν,t).

Survey of Atmospheric Data
(Ground and Satellite Monitors)

Aerosols
- Micron-size particulates
- Mie scattering

AERONET
(Mauna Kea)

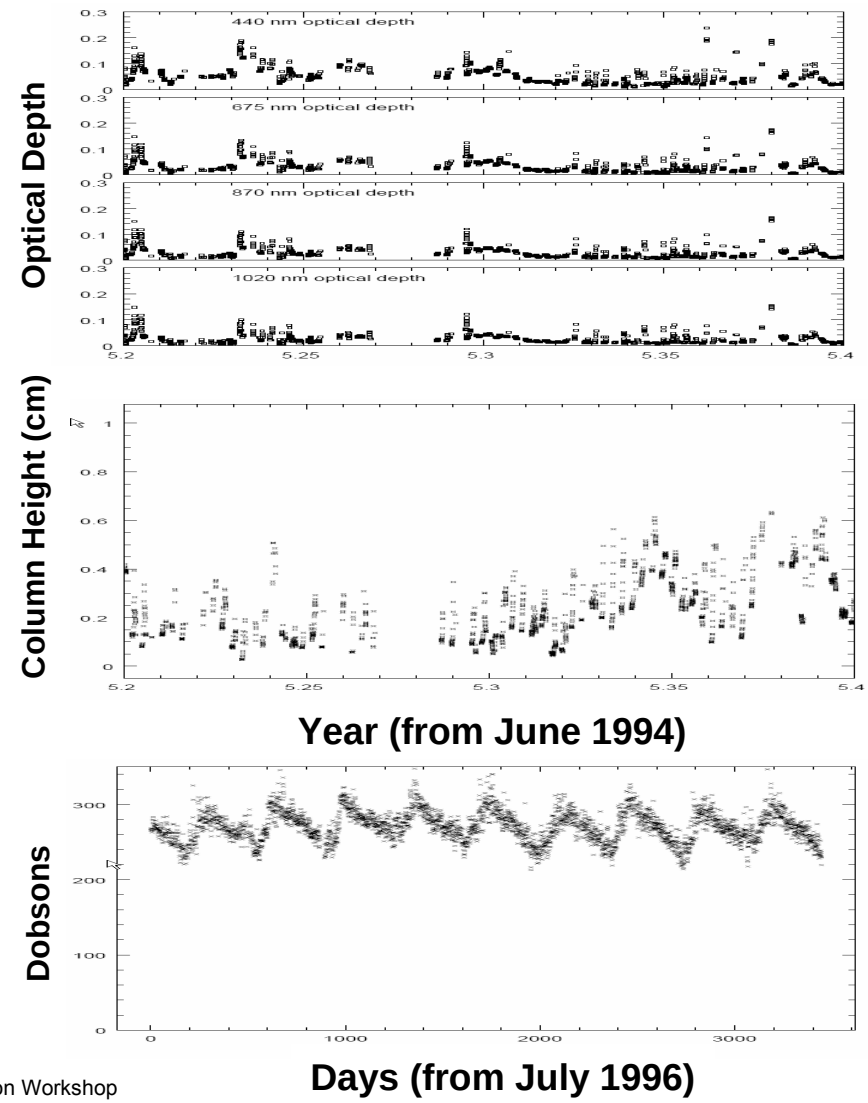
Water Vapor
- Molecular absorption

AERONET
(Mauna Kea)

Ozone
- Molecular absorption

TOMS
(Satellite)

Stubbs, et al. (2007).



Atmospheric Stability - Conclusions

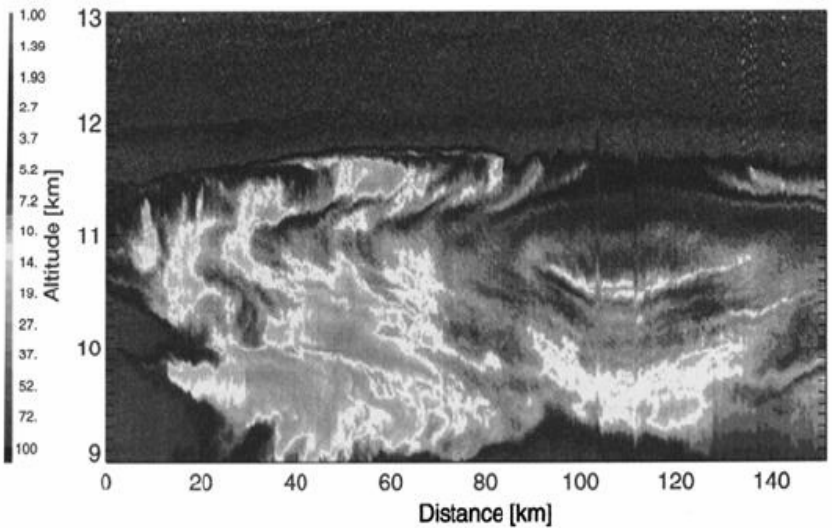
- Aerosols can change by a few percent in a day. Ozone more slowly. Both with seasonal variations.

- H_2O can change by a few percent in hours

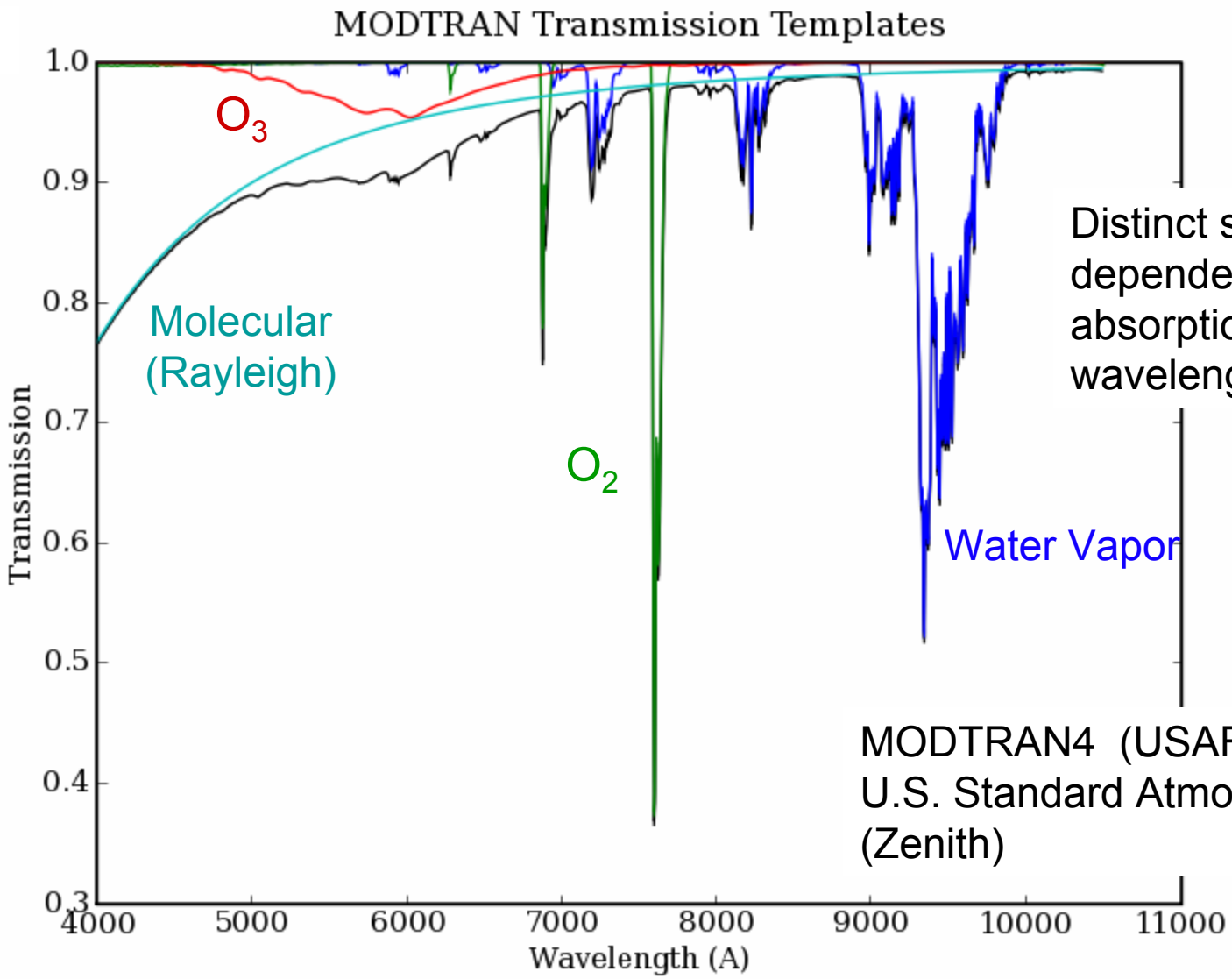
- Clouds can change minute-to-minute with intricate spatial structure

- Atmospheric throughput not always uniform across LSST 3.5° FOV

LIDAR of High Cirrus Clouds



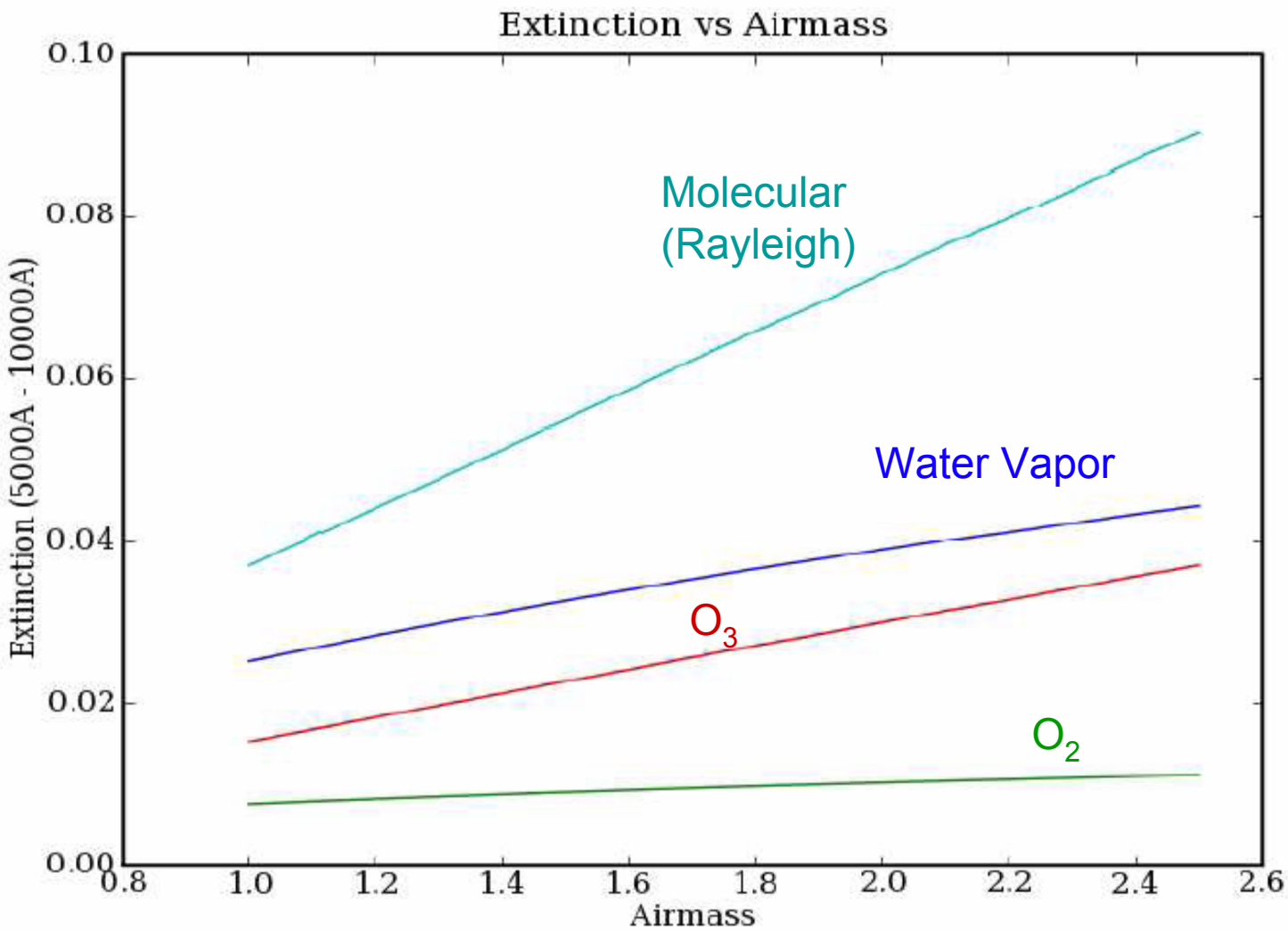
Atmospheric Signatures



Distinct signatures from dependence of absorption on wavelength and airmass.

MODTRAN4 (USAF)
U.S. Standard Atmosphere (1976)
(Zenith)

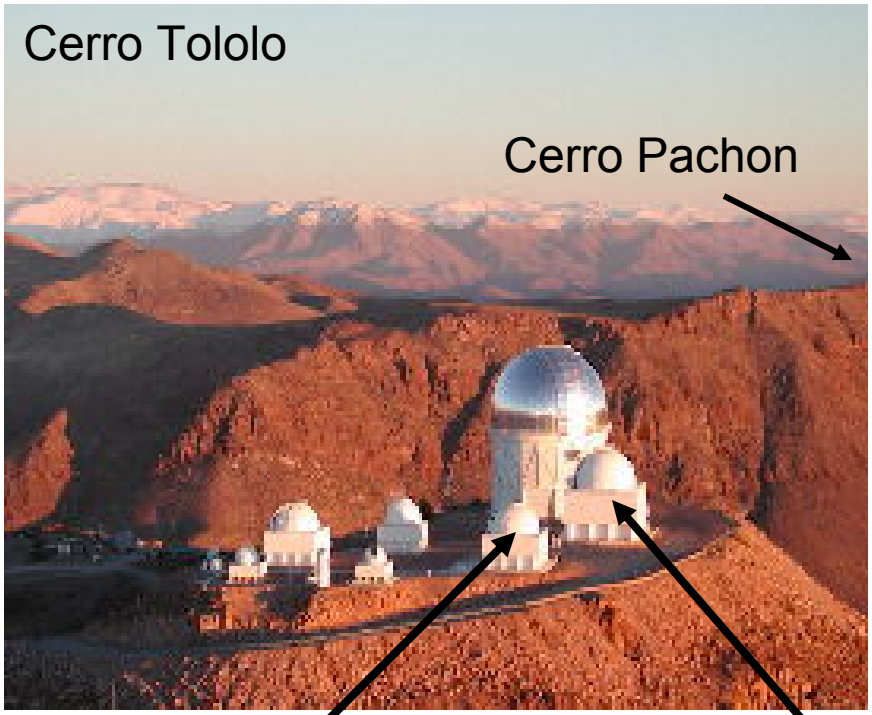
Airmass Dependence of Extinction



Observing Campaign at CTIO Tololo

NOAO Observing Proposal *Standard proposal* Panel: *For office use.*
Date: October 2, 2006 Category: EGAL - Other

Characterizing Atmospheric Absorption for Precision Photometry



SMARTS 0.9m Imager

1.5m Spectrograph

2007 Studies with the 1.5m spectrograph

Establish extraction of atmospheric parameters from spectra

Done

2008 Simultaneous observing with the 1.5m spectrograph and 0.9m imager

Calibrate 0.9m stellar photometry

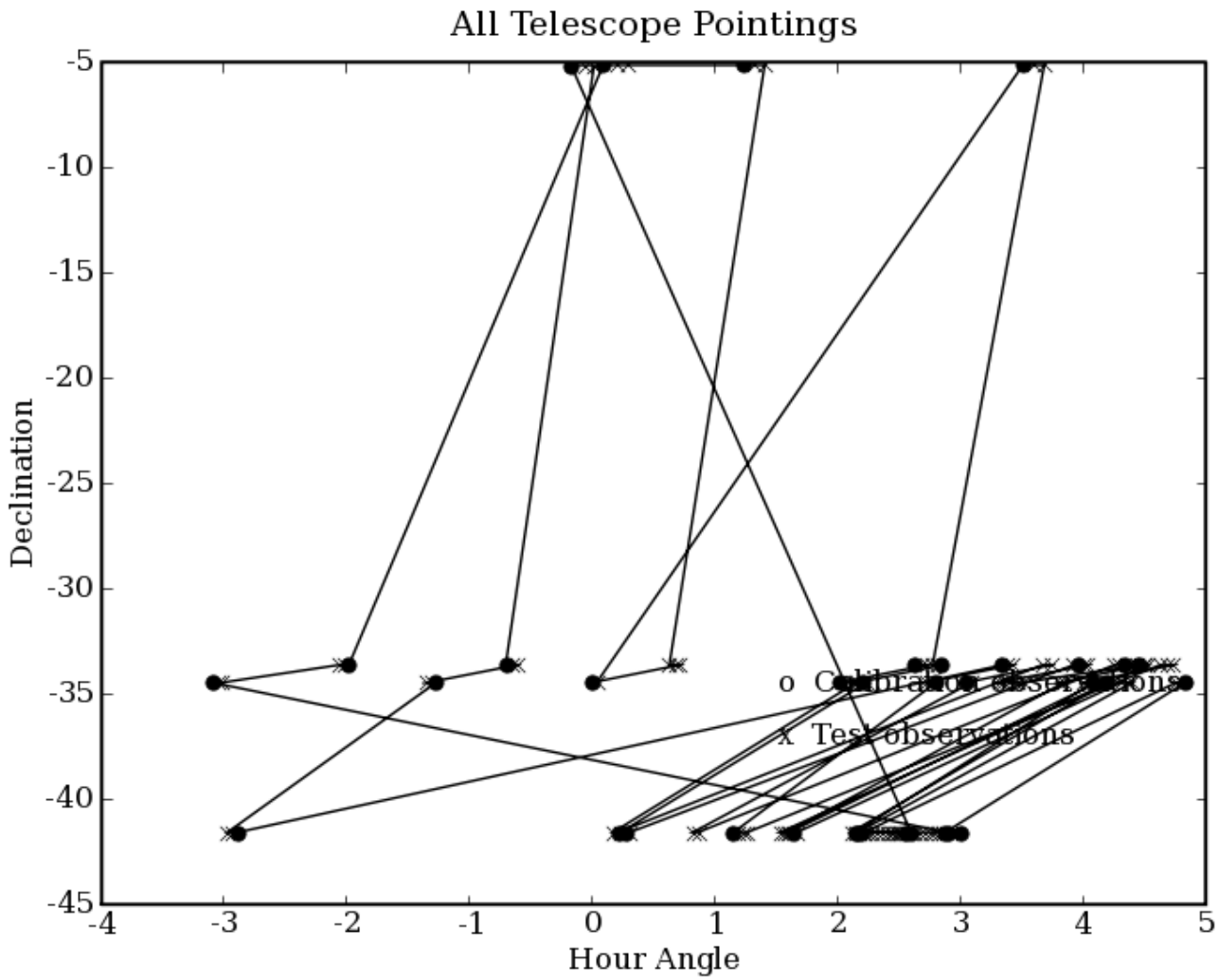
Underway

2009 Simultaneous observing with the 1.5m spectrograph and the 4m mosiac

Calibrate 4m mosiac stellar and resolved object photometry

Proposal (Sept 08)

November 2007 Calibration and Test
Telescope Visits



Feige 110 (11.8 DA)

LTT 377 (11.2 F)
CD-35 534 (10.0 F)

HD24954 (9.9F)

Calibration Fitting Procedure

Iteratively fit calibration observations:

1. Instrument Calibration. A single smooth function for each set-up

2. Target SEDs. One for each target star – fit Teff and log(g)

   Kurucz models for target A and F stars

   Blackbody with Lorentzian Balmer lines for O stars and WDs

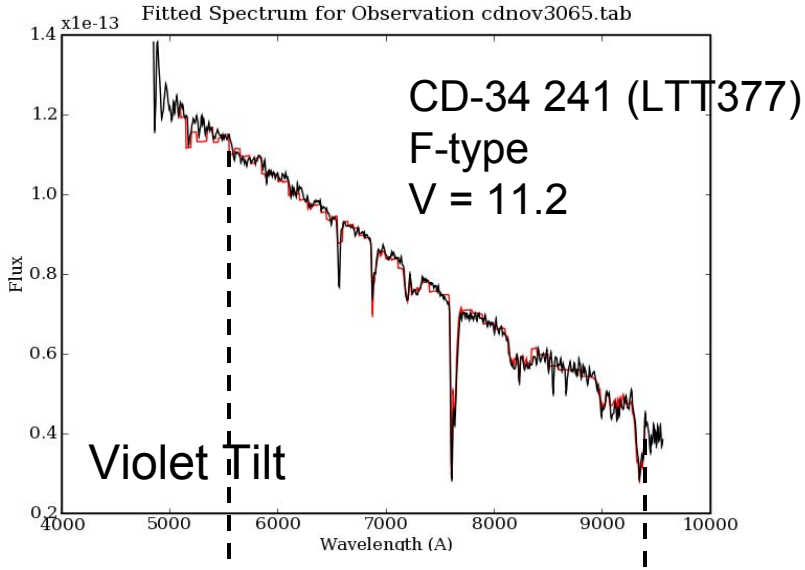
3. Atmospheric transmission:

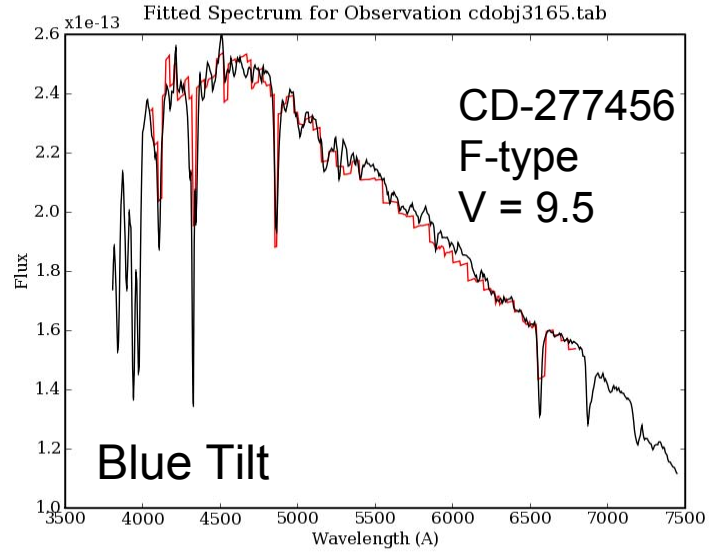
MODTRAN templates contain all airmass and wavelength dependences.

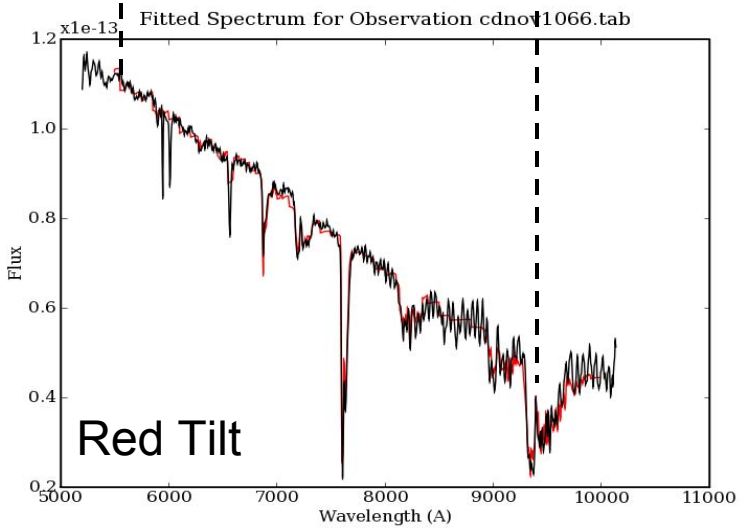
$$
\begin{aligned}
A(alt, az, t; \lambda) \;=\; & C_{gray} \times e^{(-z(alt,az)\cdot\tau_{aerosol}(alt,az,t))} \times \\
& \times (1.0 - C_{BP} \times \text{Rayleigh scattering}(z(alt,az);\lambda)) \times \\
& \times (1.0 - \sqrt{C_{BP}} \times \text{molecular absorption}(z(alt,az);\lambda)) \times \\
& \times (1.0 - C_{ozone} \times \text{ozone absorption}(z(alt,az);\lambda)) \times \\
& \times (1.0 - C_{H2O}(t) \times \text{water vapor absorption}(z(alt,az);\lambda))
\end{aligned}
$$

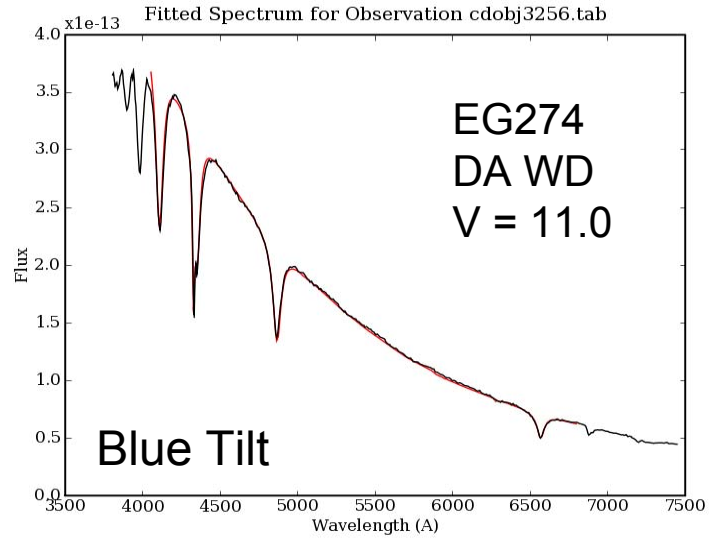
Coefficients determined by vertical column heights when observations are made.

Example Spectra and Fits

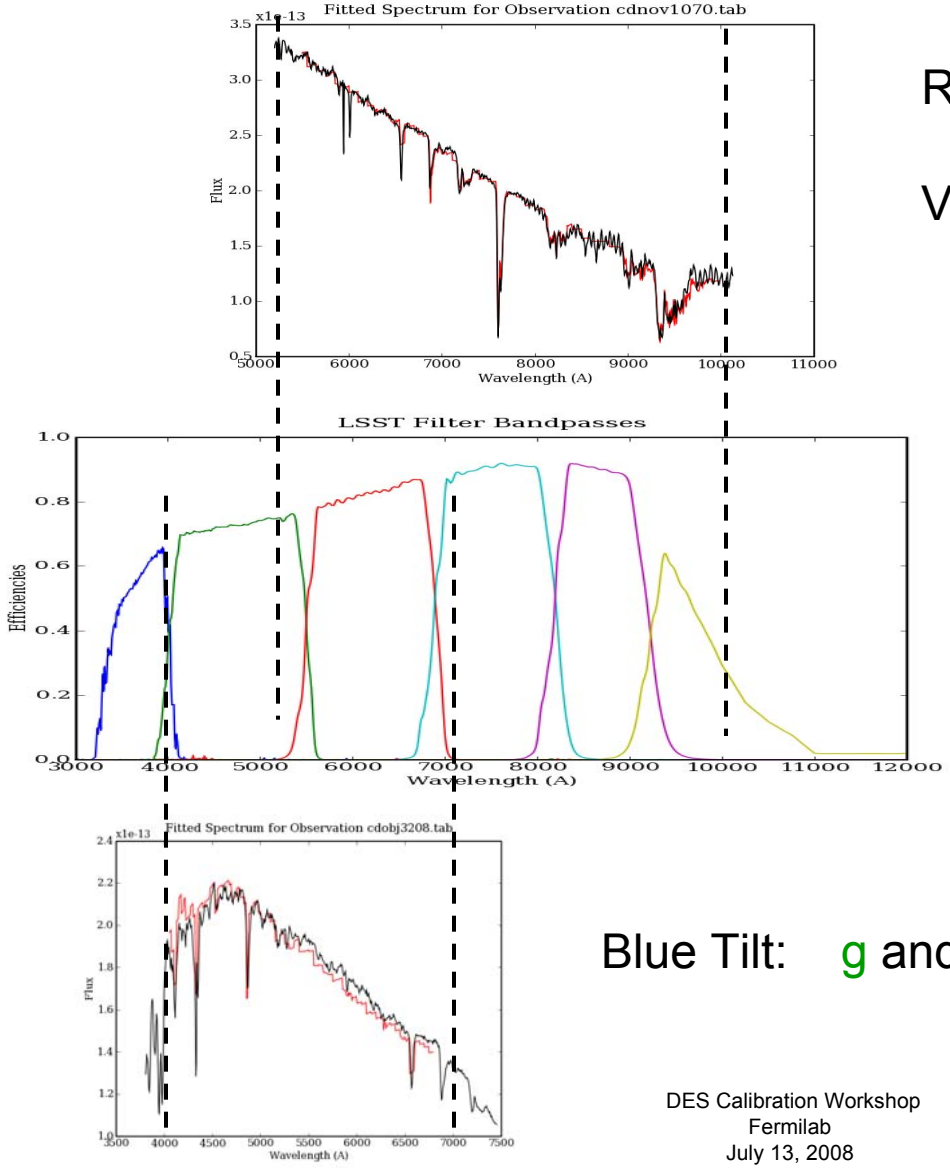








Synthetic Photometry



Red Tilt: r, i, z, and y4 bands.

Violet Tilt: r, i, and z bands.

No measurements in u-band.

Blue Tilt: g and r bands.

Data Acquisition and Handling

Calibration Stars – Small set of stars (4-6) used to determine and confirm calibrations

Calibration Observations

Minimal number needed to rigorously determine atmospheric parameters

Test Observations

Observations used to check internal consistency

Blind Test Stars – Independent set of stars used to verify calibration

Data only “opened” after full analysis of Calibration Stars

Slowly Varying Components

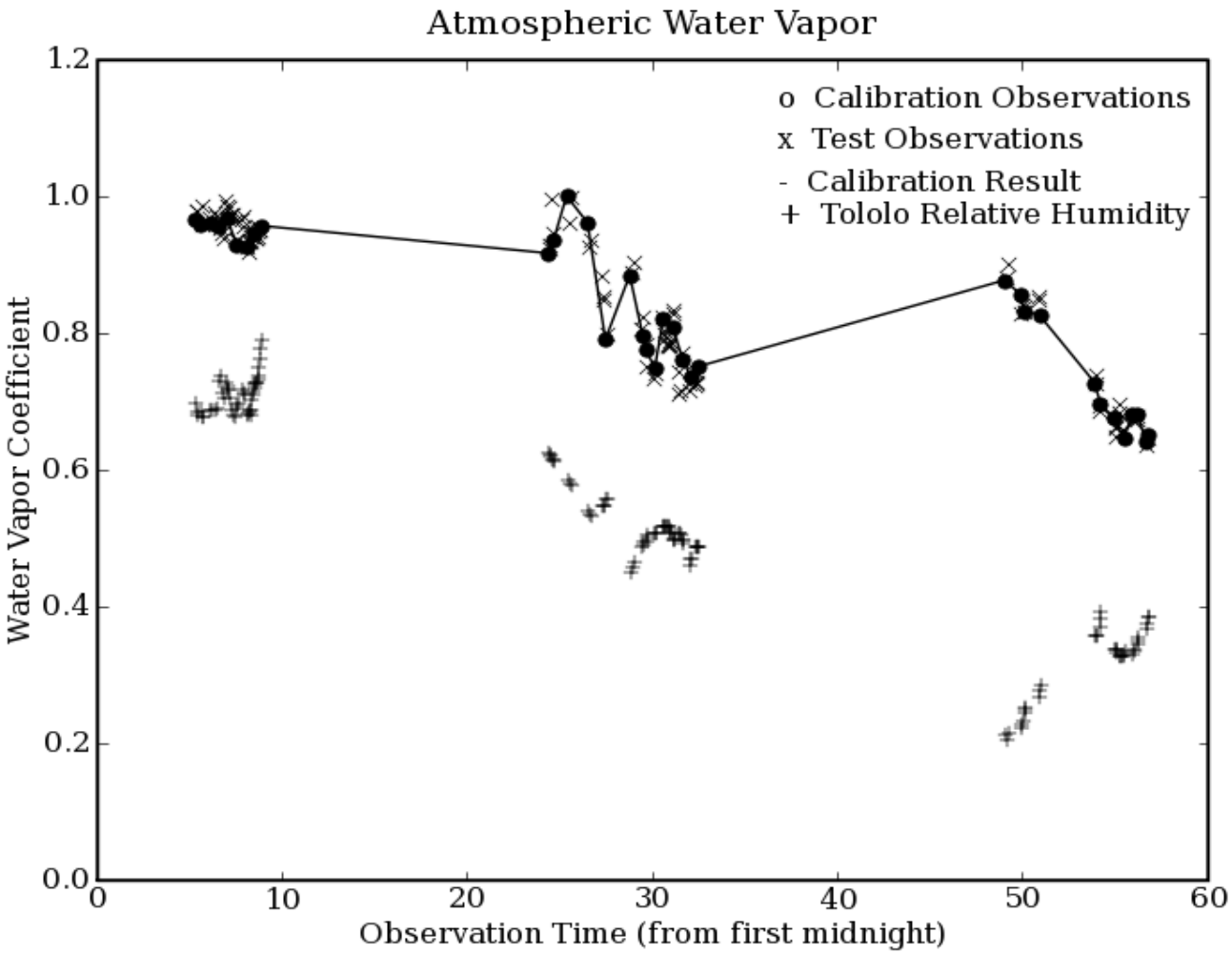
Stable over 3-night observing periods in April and November 2007.

Summary of Calibration Fit Results

Parameter	Symbol	Units	Apr Value	Nov Value
Barometric Pressure	C_{BP}	None	0.901	0.854
Ozone Vertical Height	C_{ozone}	None	0.827	0.804
Aerosol Vertical Height	τ_0	None	0.015	0.019
Aerosol Temporal	τ_1	hr^{-1}	0.0001	0.0004
Aerosol Spatial	τ_2	rad^{-1}	0.0000	0.0003
Aerosol Index	α	None	-0.931	-0.999

November 2007 Calibration
Precipitable Water Vapor

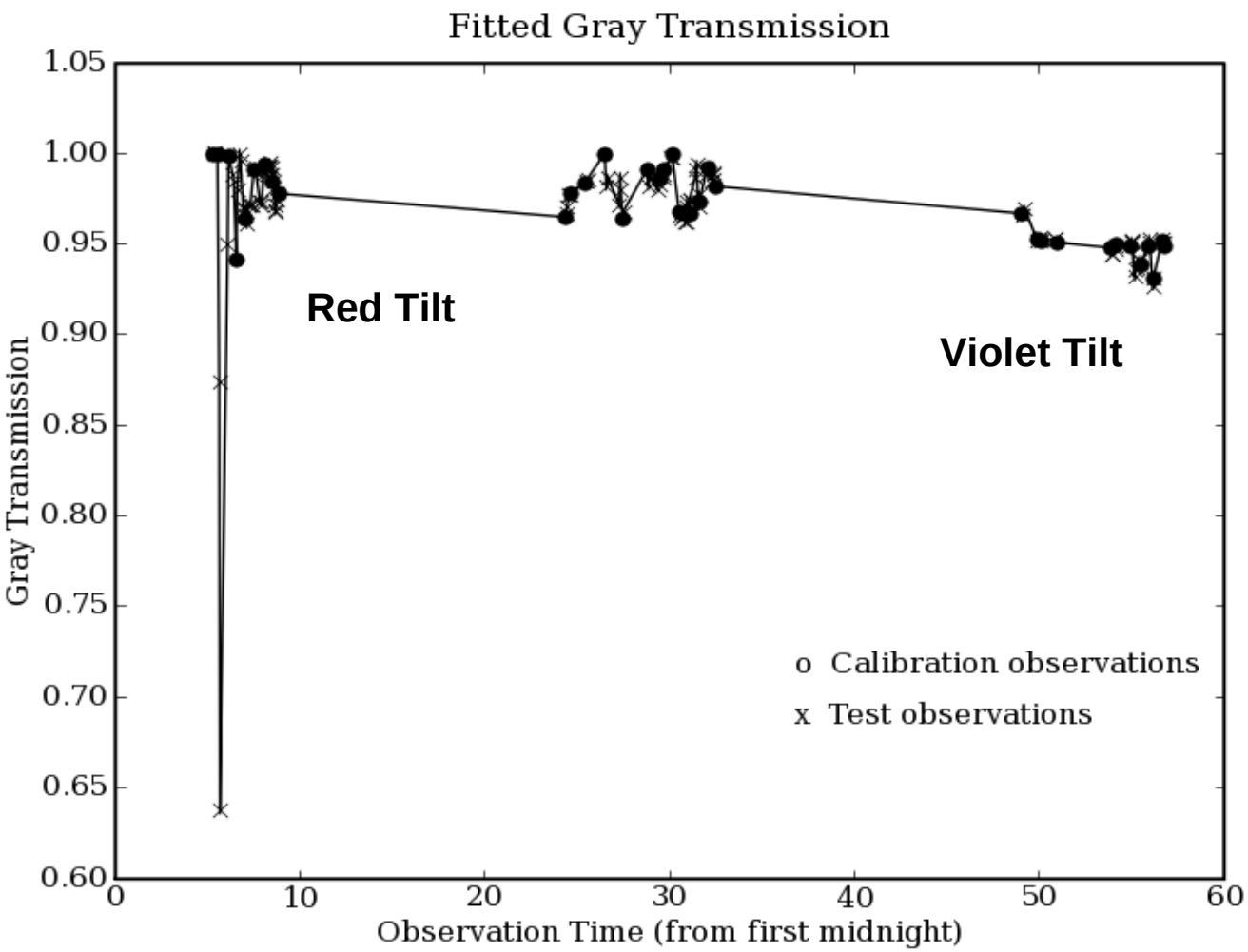
Variable on time scale of an hour.



Linear interpolation in time requires calibration point every 15-20 mins to meet SRD specifications for stability in y band.

November 2007 Calibration
Gray Extinction (Clouds)

Rapid variations large compared to SRD specs for photometric precision.

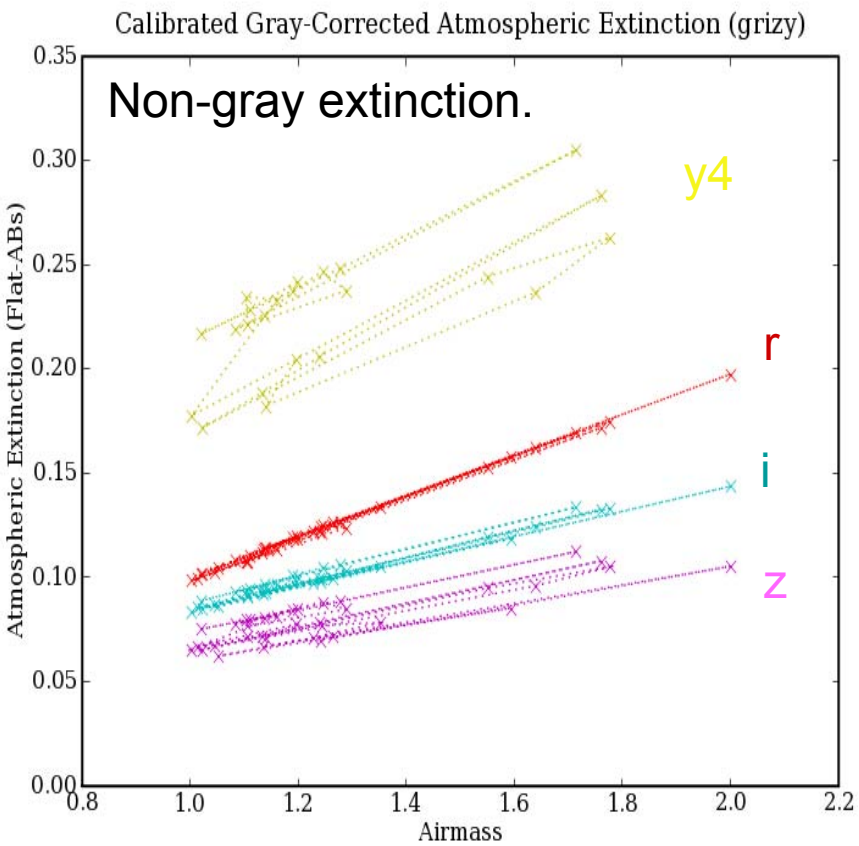


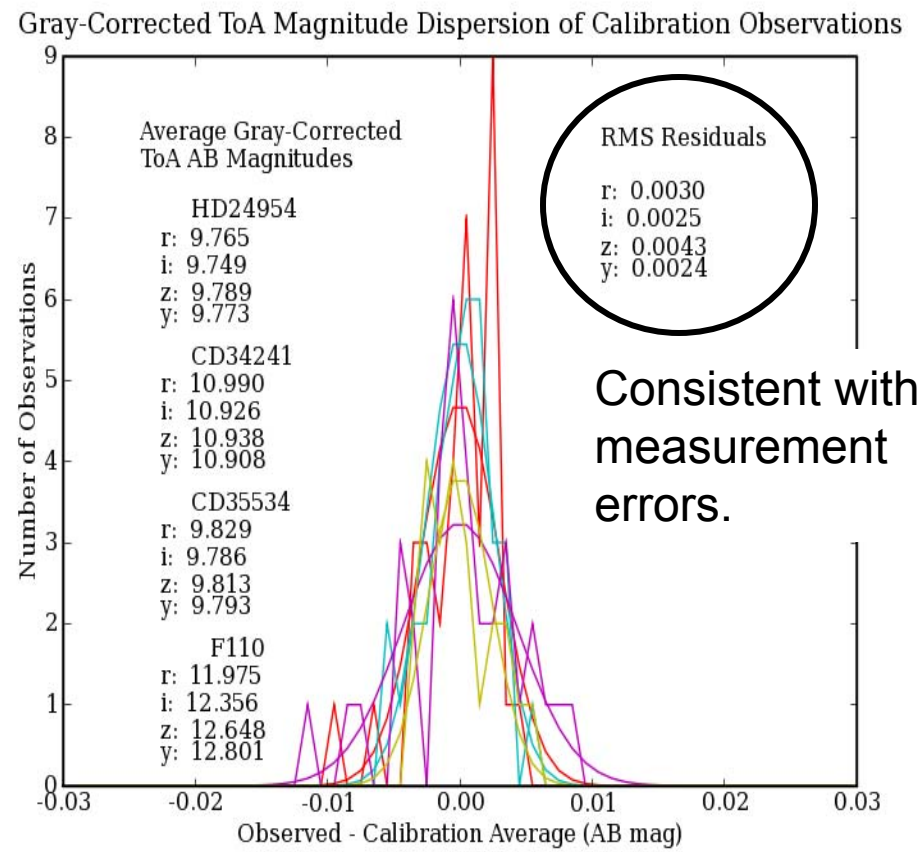
Extrapolation of C_{gray} from calibration observations to other points in space and time does not meet SRD specifications.

Calibration Observations

A separate gray coefficient for each calibration observation.

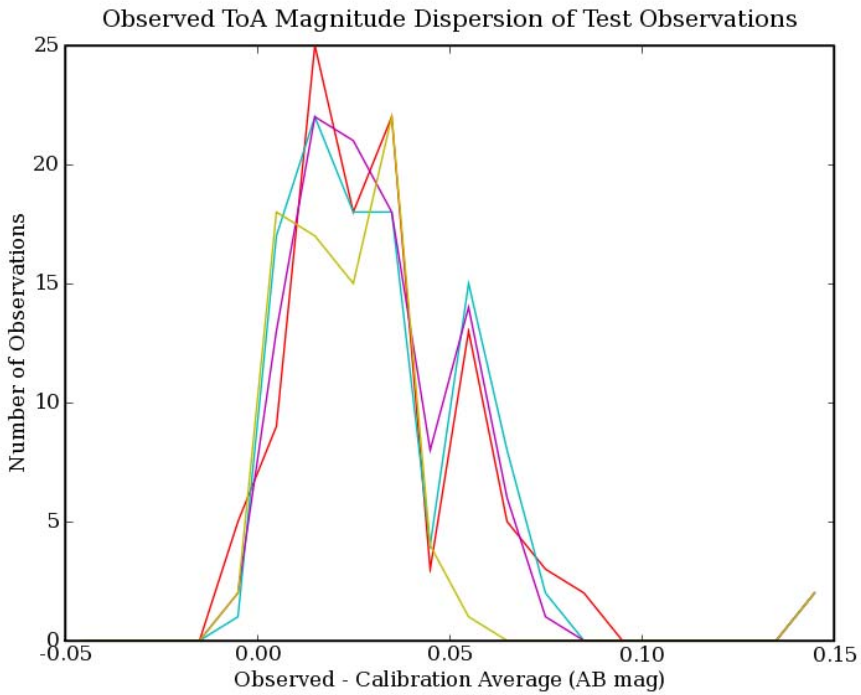
This is the best that could be done if the auxiliary telescope tracked LSST with no extrapolation in time or coordinate across the sky.



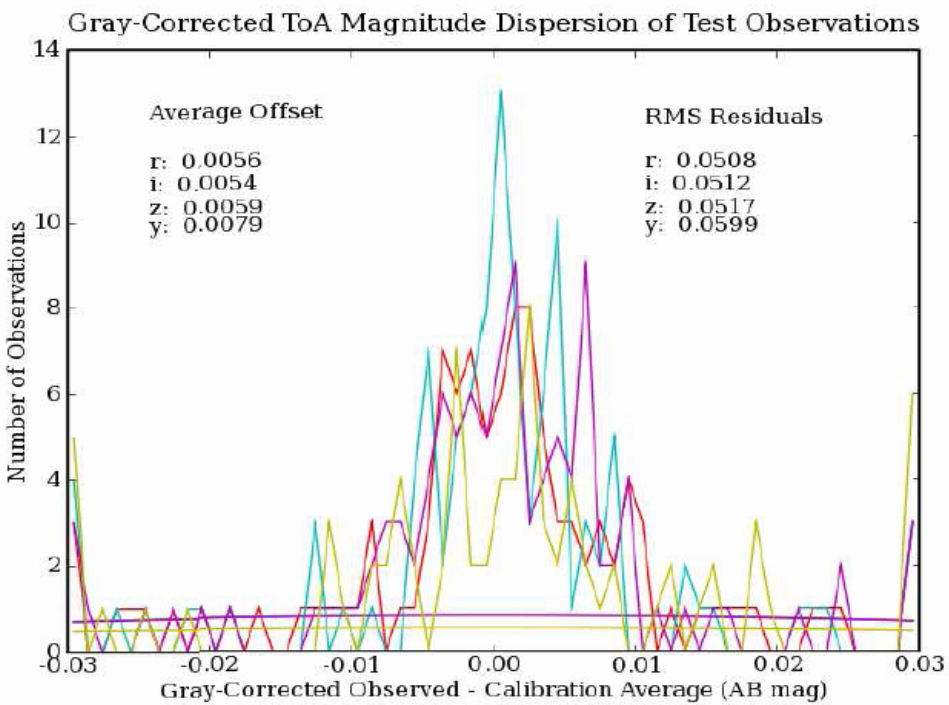


Test Observations of Calibration Stars

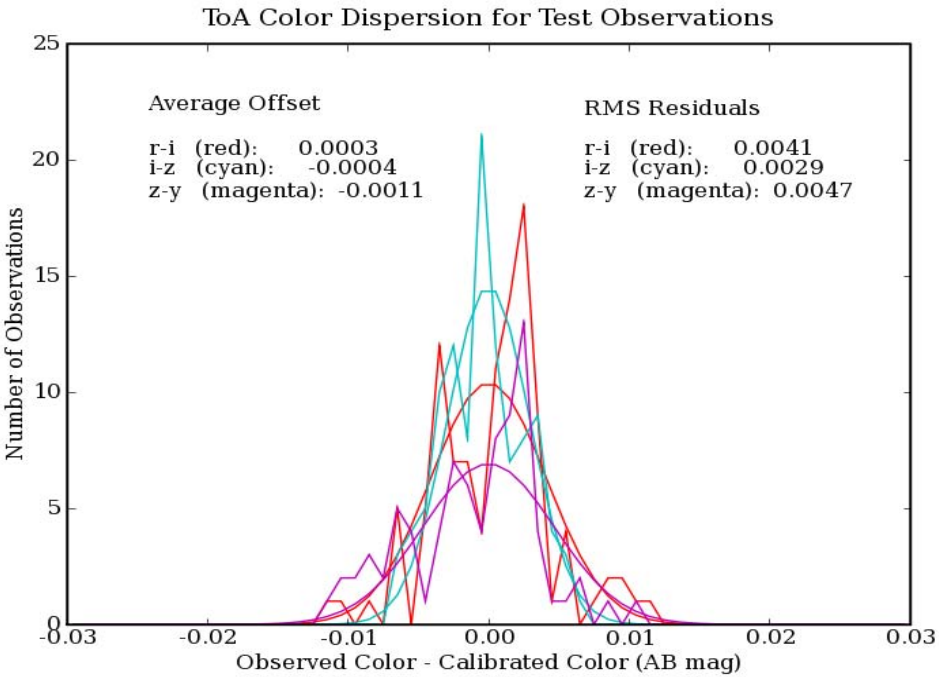
Apply non-gray calibration corrections …



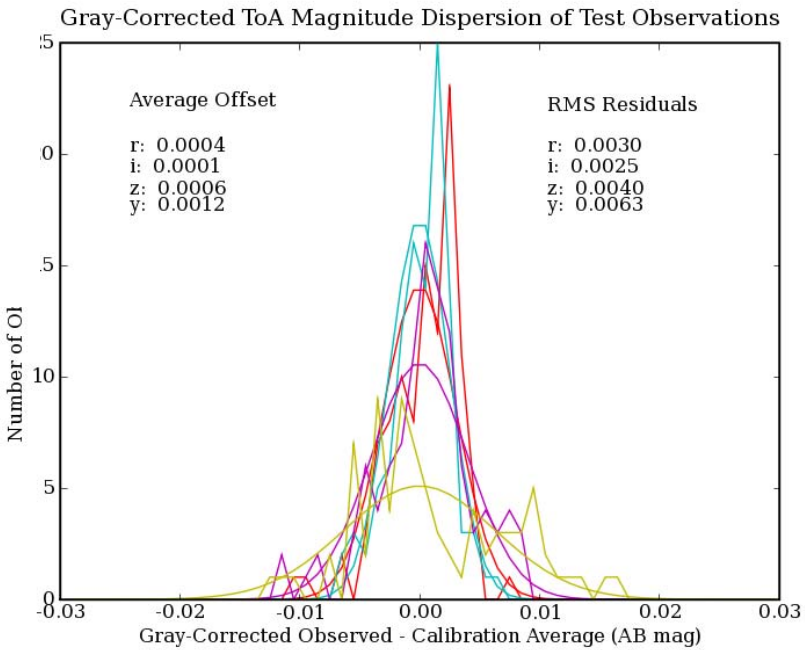
Try to interpolate the gray correction from calibration observations …



Colors of Test Observations



And if we "cheat" and look at fitted gray corrections for test observations …



Conclude that the model accounts for all components; residual extinction is no greater than ~ 3 millimags.

Summary of Dispersion Measurements

Table 5: Summary of Gray-Corrected Dispersion Measurements (10^{-3} AB Magnitudes)

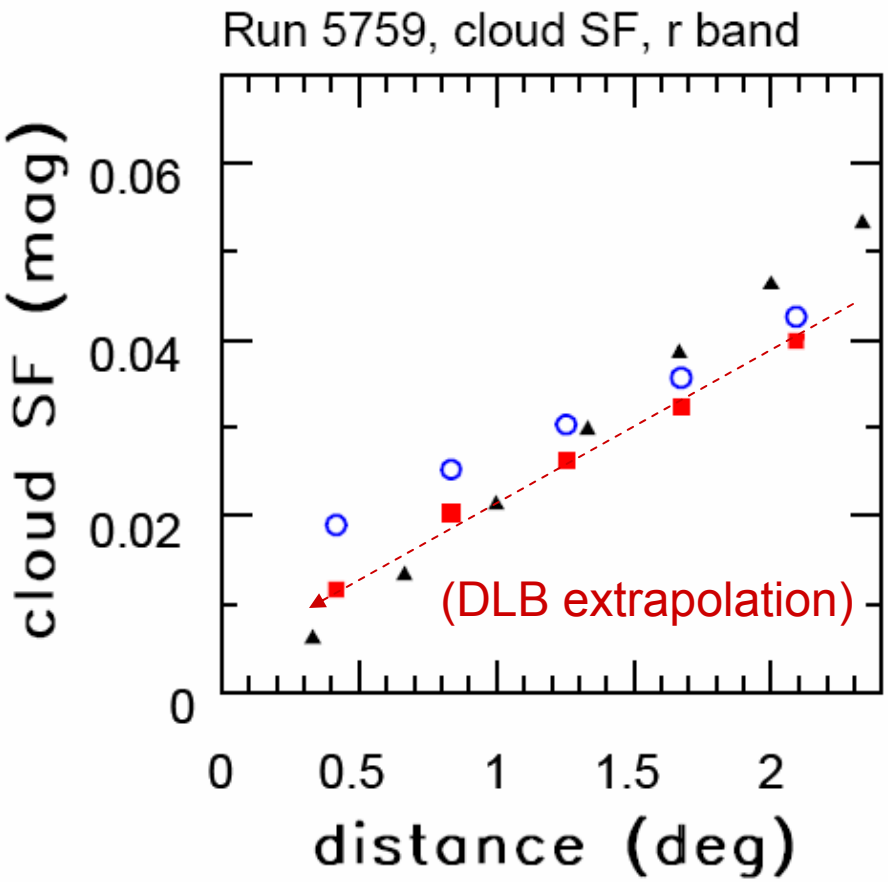
Data Set	g	$g-r$	r	$r-i$	i	$i-z$	z	$z-y$	y
Apr Cal Magnitudes	2.3		4.0						
Apr Control Magnitudes	1.6		3.8						
Nov Cal Magnitudes			3.0		2.5		4.3		2.4
Nov Control Magnitudes			3.0		2.5		4.0		6.3
Nov Blind Magnitudes			3.5		2.2		4.3		8.1
Apr Control Colors		5.1							
Nov Control Colors				4.0		2.9		6.6	

Residual uncalibrated variation of ozone depth?

We expect auxiliary telescope data to calibrate wavelength-dependent components of extinction with precision that meets SRD specs.

Cloud Structure – Some Data from SDSS

Data from a run with “smooth” cloud cover of 1-2 magnitudes. Ivezic, et al (2006)



In this case, gray zero-point dispersion ≤ 0.01 mag (rms) for separations ≤ 0.25 degree (one LSST CCD 14' × 14').

Will have ≥ 100 stars on each CCD to measure pattern of gray extinction (<u>after correcting for wavelength dependent extinction</u>).

→ Observing tests on Tololo 0.9m imager with 13' × 13' FOV.