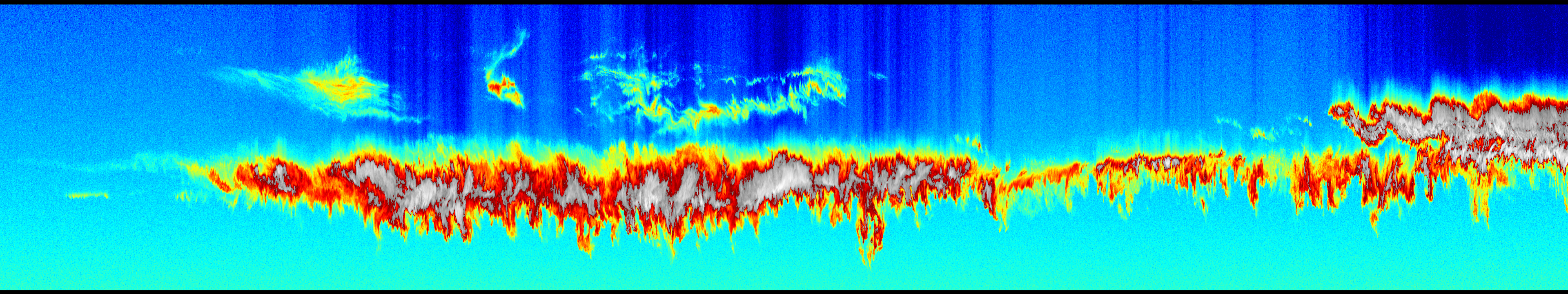
A Path to NIST Calibrated Stars over the Dome of the Sky



April 18, 2012

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NIST

Astronomical Photometry: Extinction Record

"It is impractical to determine the extinction thoroughly and accomplish anything else."

- Stebbins and Whitford (1945)*

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Not a warning, a measurement philosophy!

NIST Stars

Spectral irradiance calibration ($W/m^2/nm$) of bright stars (V<5.5) to NIST standards

Initially dozens, ultimately ~100 objects

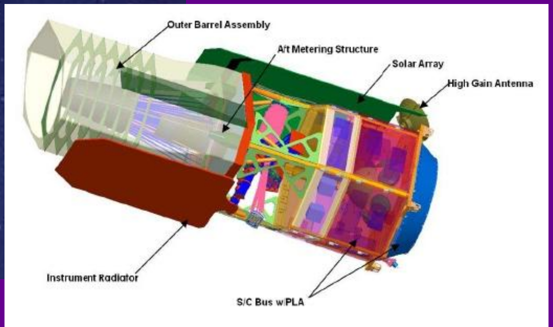
- Vega, Sirius, 109 Vir, ~20 targets from NGSL
- Please contribute your favorite star!

Initially < 1% accuracy per nm from 400-1000nm

Biggest known obstacle: Atmospheric T

Applications of Absolute Standard Stars

- calibrating Earth-observing spacecraft, including weather and climate
- calibrating ground- and space-based telescopes
- SSA sensor test and calibration,
  - characterization of low Earth orbit objects
- Missile defense sensors
- Geospatial intelligence sensors



Instruments that can be calibrated using standard stars:

Upper Left: NOAA GOES-R Satellite

Far Left: SBIRS Ballistic missile launch detection satellite

Left: Wide Field InfraRed Space Telescope (WFIRST)

Atmospheric Transmission: Two Categories, Two Instruments

Slowly varying with wavelength

- Clouds – rapid temporal and angular variability
- Aerosols – confusion with O_3 absorption

Measurement Solution:

Calibrated LIDAR

Rapidly varying with wavelength

- H_2O absorption – significant temporal variability
- O_2 absorption – stable and easily modeled

Instrumental Solution:

Calibrated Spectrophotometry

Astronomical Extinction Spectrophotometer (AESoP)

- For bright stars, a large aperture is not required
- AESoP is an objective spectrophotometer
  - 106mm Takahashi refractor
  - Paramount ME eq. mount
  - 90 l/mm transmission grating mounted behind entrance aperture
  - 100mm diam. Invar aperture

    Measured area: 7827.17 +/- 0.01 mm^2
- No optical elements other than an order separating filter) after the telescope objective lenses
- Sci-In photometric shutter
- Photometric precision is fundamentally limited by scintillation

- AESoP Key Parameters
  - Free spectral range
    - Shortpass (2nd order): 320 nm– 550nm
    - Longpass: 525nm – 1050nm
  - Spectral resolution 0.6 nm,

    R = 1100 at 650nm
  - Pixel resolution 0.28nm at 650nm

AESoP Calibration

CAL – the irradiance transfer standard

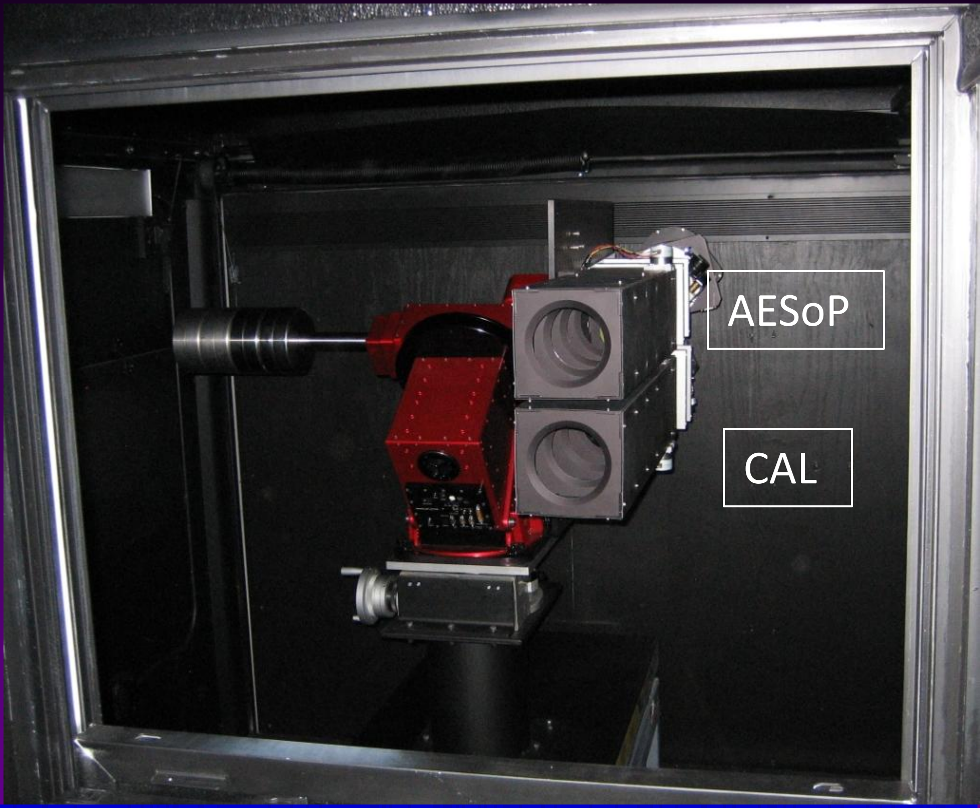
Nearly identical to AESoP but:

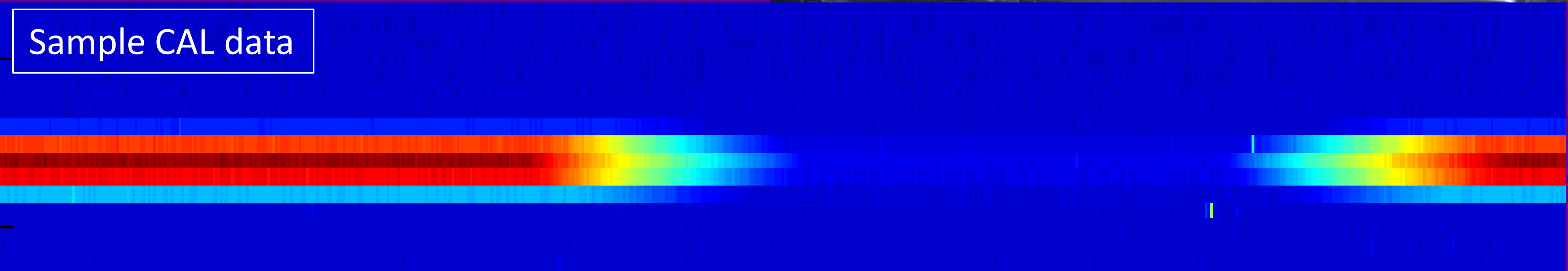
- No grating or order blocking filter
- Fabry lens makes pupil image on CCD
- CCD read out in TDI mode (see poster)
- Easily removable from mount
- Calibrated at NIST

Proof of concept detector achieved

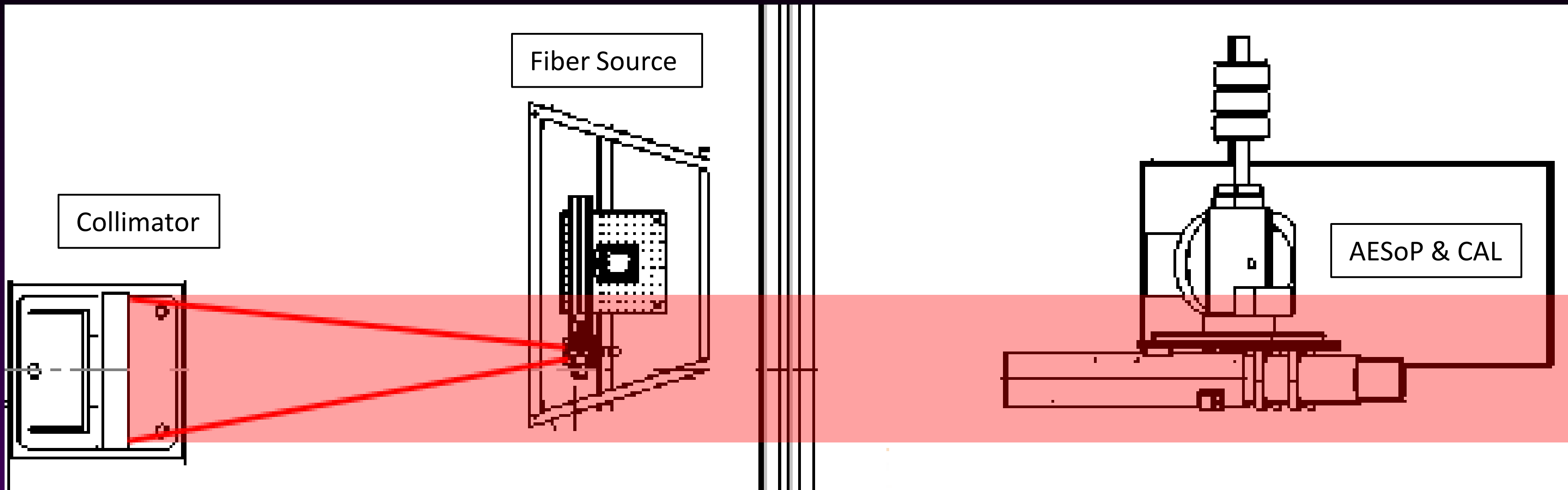
NEP < 100 aW/√Hz at 550nm

New detector expected < 20 aW/√Hz





AESoP Calibration



In calibration mode:

- Trailer roof closed
- AESoP and CAL both pointed at collimator mirror
  - Fiber at collimator focal point is fed by a monochromator
- AESoP and CAL illuminated one wavelength at a time to transfer irradiance calibration from CAL to AESoP
- System can translate vertically to assess illumination variations
- CAL only observes this or horizon calibrator
  - CAL is otherwise closed to protect optics

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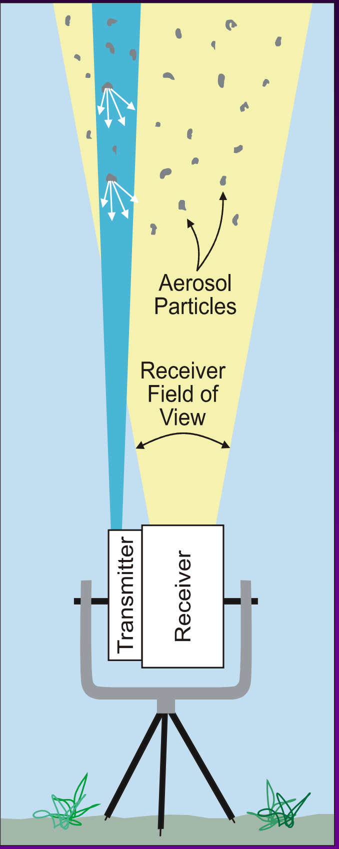
Basics of LIDAR

LIght Detection and Ranging – laser analog to radar

$$N_\gamma(r) = \frac{N_0 \eta A}{2r^2}\left[\frac{3}{8\pi}\beta_M(r) + \frac{P_\pi(r)}{4\pi}\beta_P(r)\right]e^{-2\int_0^r(\beta_M+\beta_P+\alpha_M+\alpha_P)dr'}$$



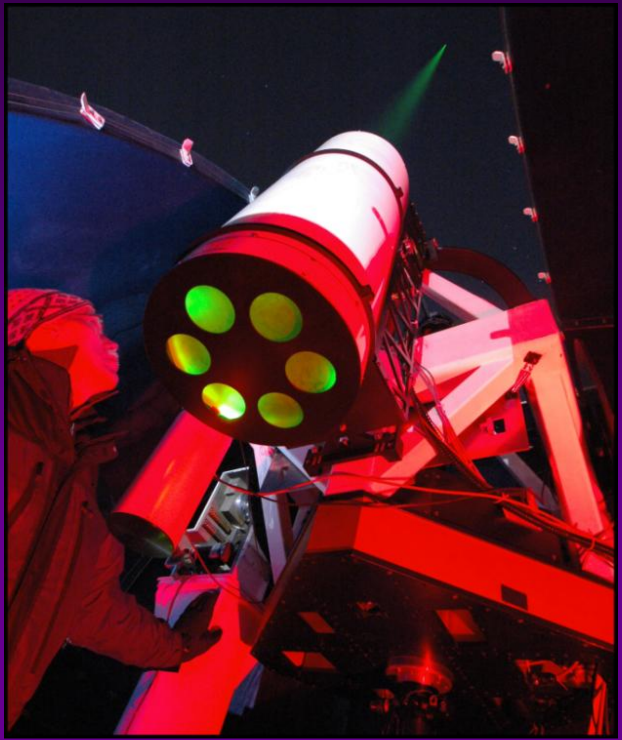
Sensitive to:

Rayeigh scattering

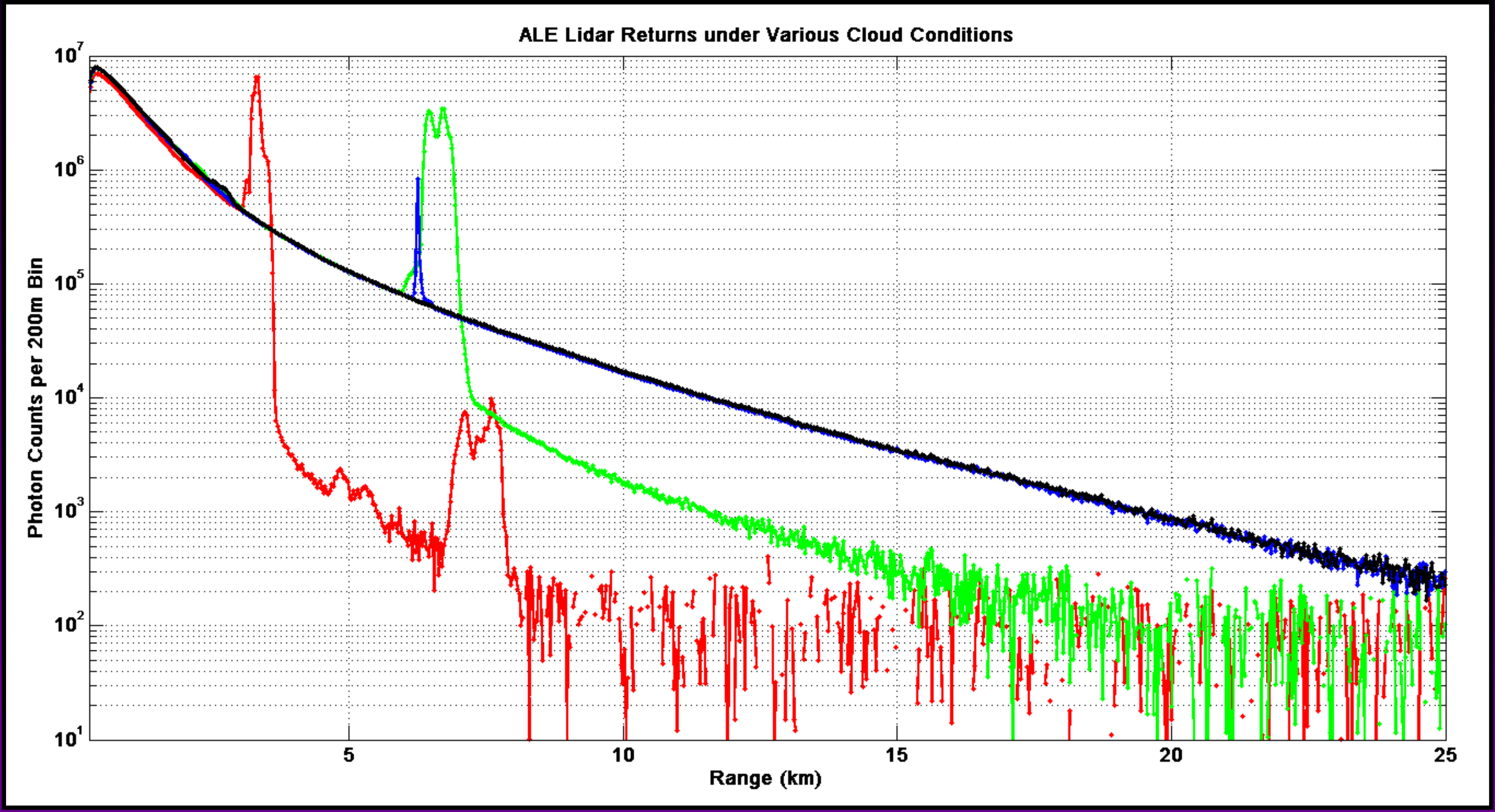
Mie scattering

Molecular and aerosol absorption

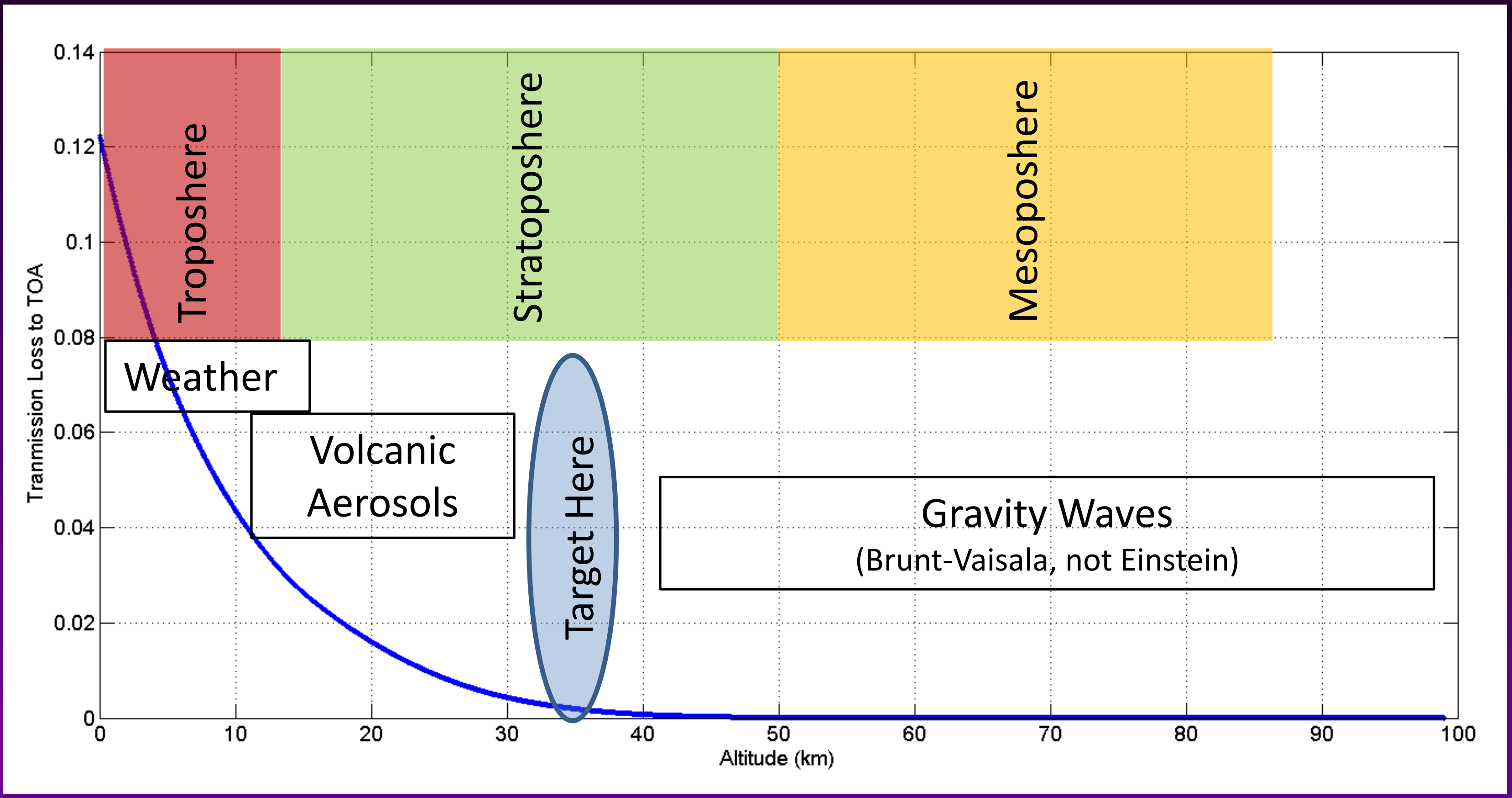
Time-gated return yields range



The Stratosphere

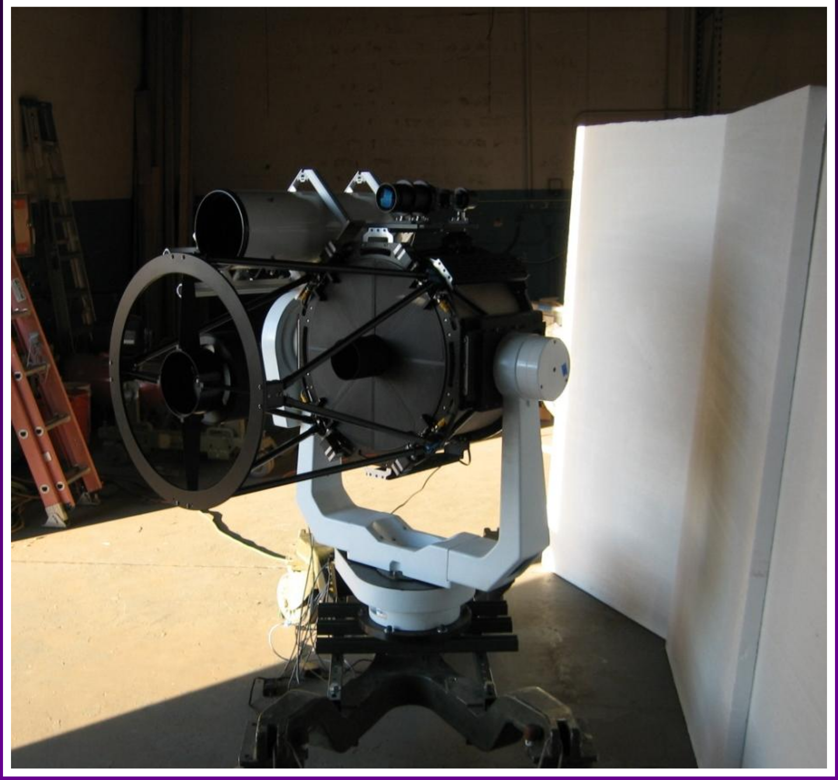


Target the Stratosphere



Facility Lidar for Astronomical Monitoring of Extinction (FLAME)

- FLAME simultaneously transmits 3W at 1064nm, 2W at 532nm and 1.5W at 355nm
- 6 ns pulses at 1500Hz emitted from 200mm diameter transmitters
- Return below 10km collected with three 75mm refractive short range receivers
- Return from high altitude are collected with 500mm long range receiver
- Long range photons split with dichroics and sent to individual photomultipliers
- DESIGN GOAL: > 1 x 10^6 photons/minute from above 30km



Calibrating FLAME

$$N_{\gamma}(r) = \frac{N_0 \eta A}{2r^2}\left[\frac{3}{8\pi}\beta_M(r) + \frac{P_{\pi}(r)}{4\pi}\beta_P(r)\right] e^{-2\int_0^r (\beta_M + \beta_P + \alpha_M + \alpha_P)\, dr'}$$

Transmitter:

- Calibrated telescopes (one for each wavelength) in trailer
- FLAME transmits at these to establish link to power meter
- Current design testing off-axis mirror vs. Fresnel lens
- Photodiode inside an integrating sphere for detectors

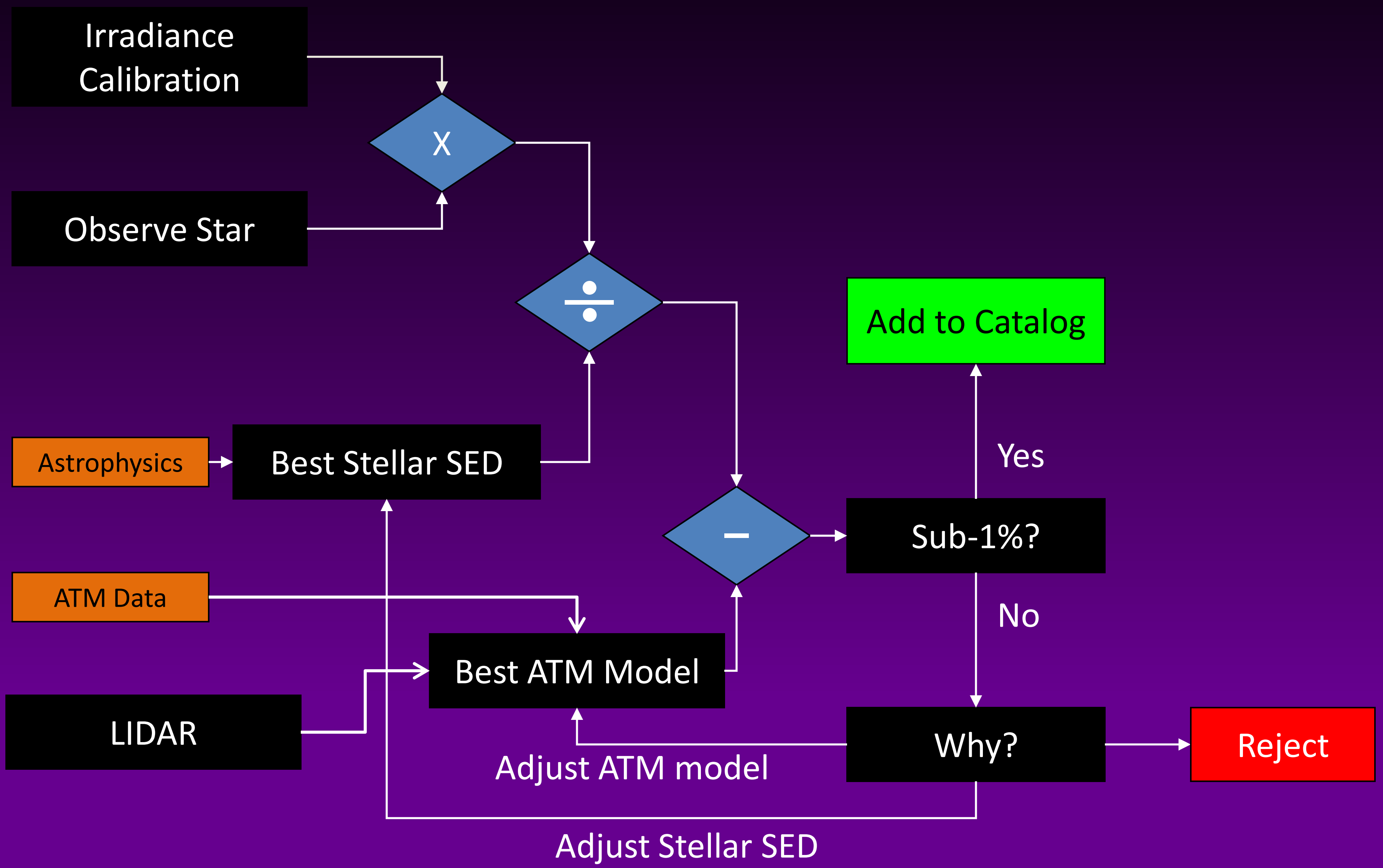
Receivers:

- CAL with laser-line filter for FLAME calibrated at each laser wavelength
- Use bright stars and twilight sky for calibration source

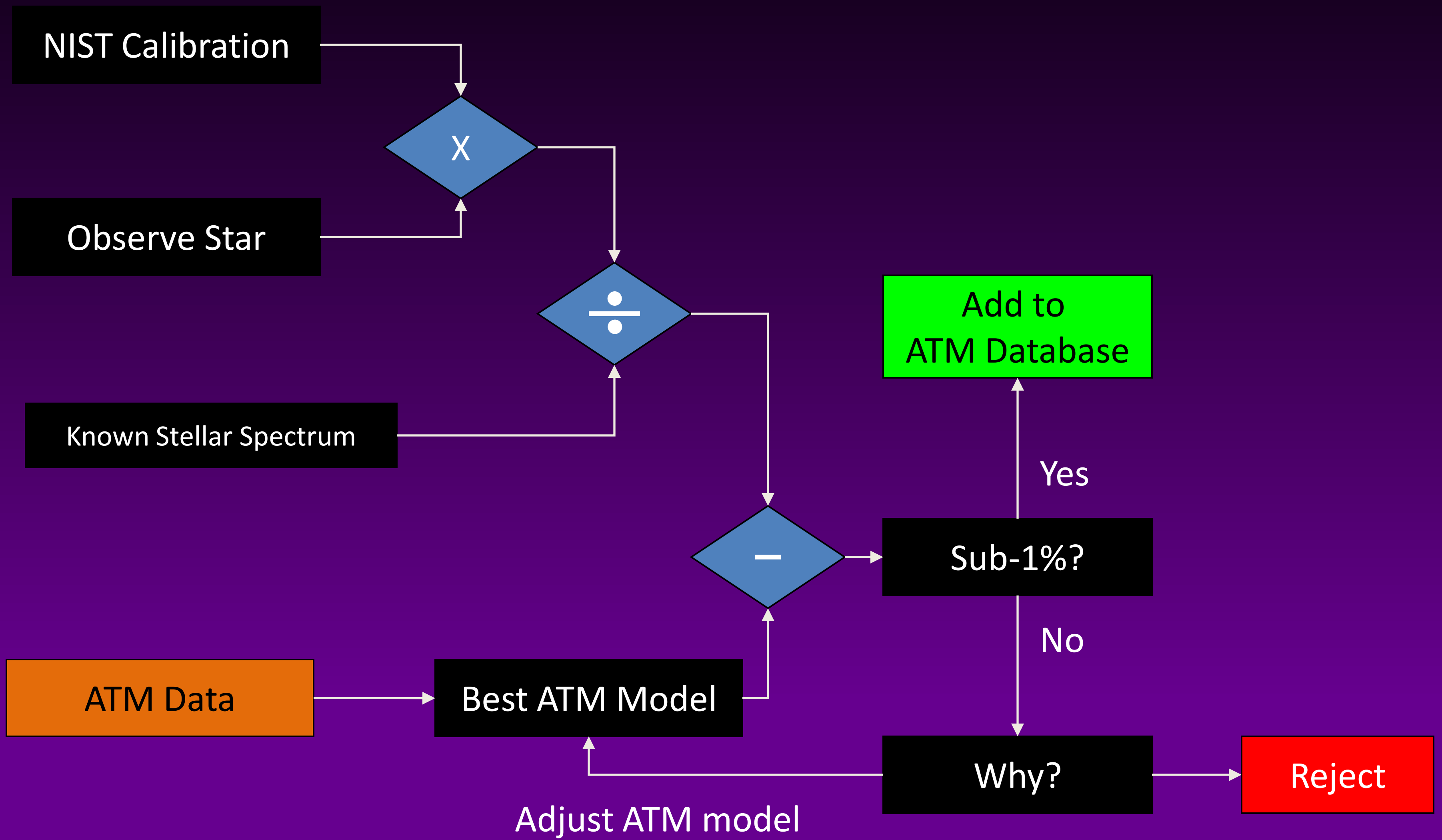
Scattering:

- From sonde profile

Making and Maintaining Absolute Standard Stars

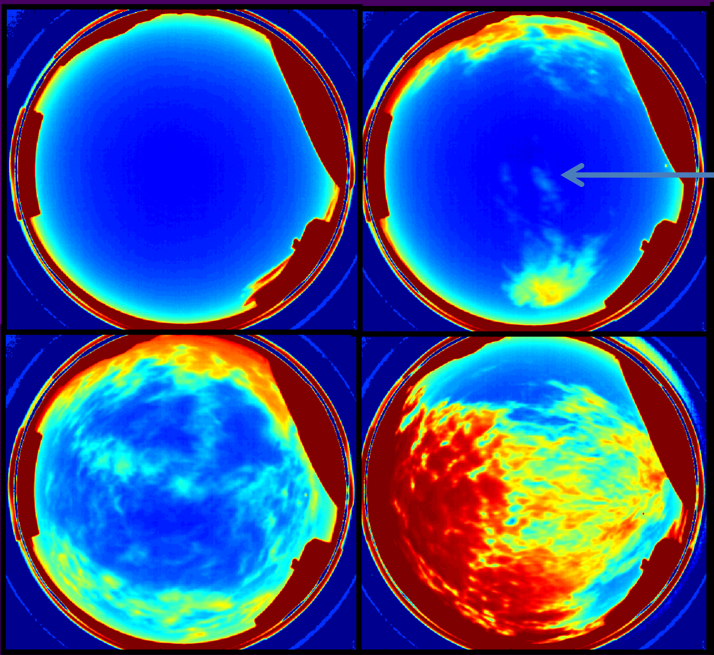


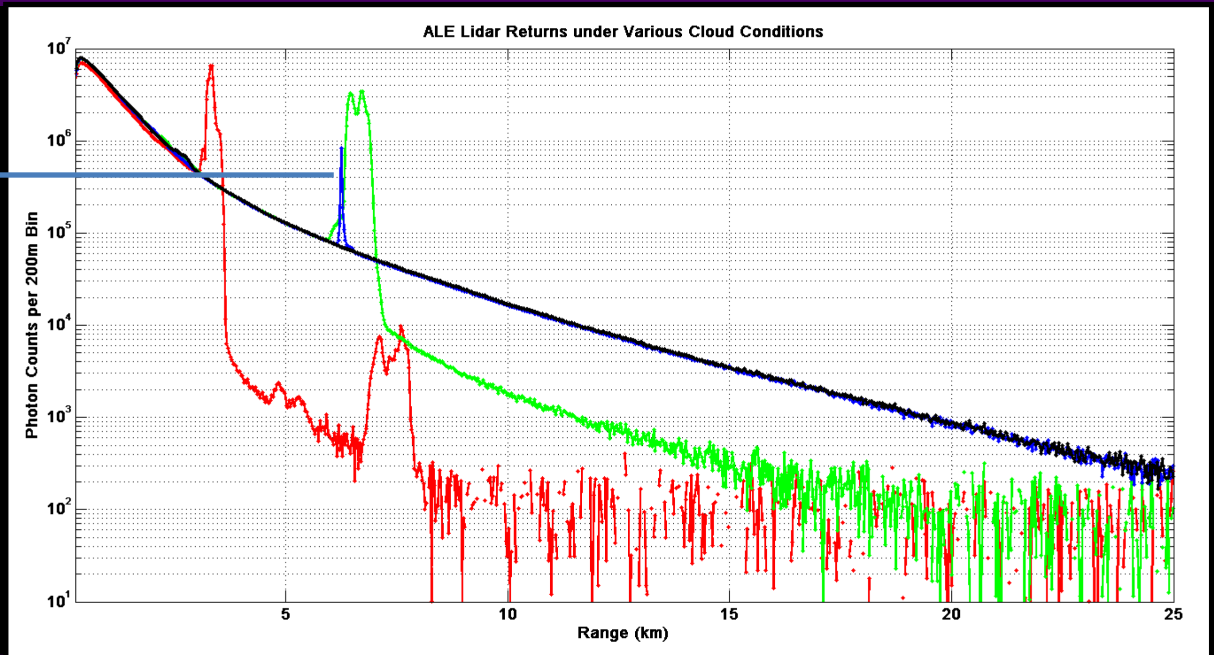
Monitoring Transmission for Larger Science Telescope



Lidar plus Thermal IR Imaging

- Off-the-shelf uncooled bolometer arrays have the potential to detect the thermal radiance of clouds with $\tau < 0.01$
- Lidar can measure cloud transparency very well, but only in beam
- Thermal IR can measure radiance over wide field
- Establish radiance->transparency relationship at beam to enable correction of wide-angle transparency variations





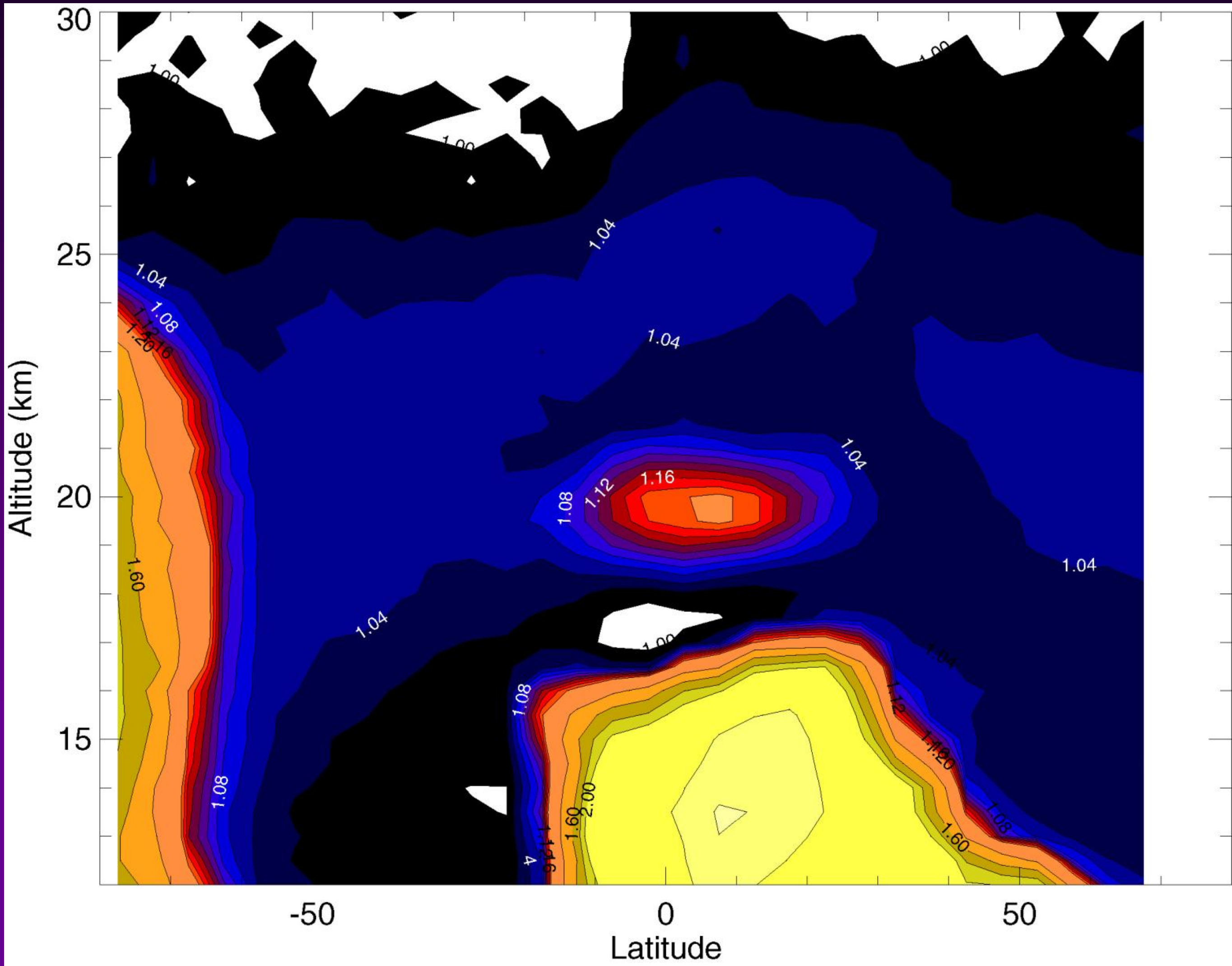
Summary

- Bright stars absolutely calibrated to NIST spectral irradiance ($W/m^2/nm$) can aid calibration of a wide variety of sensors
- Atmospheric transmission is the critical limitation
  - Directly measure the air between the telescope and star
- Production of these will begin this summer using:
  - Calibrated spectrophotometry
  - Calibrated lidar
- Combinations of complementary instruments can constrain atmospheric transmission at an observatory site
  - Atmospheric metadata stream is a natural byproduct
  - Valuable dataset to more than just astronomers

Why so high?

Calipso average aerosol to molecular backscatter

Aug. 2008



Why not higher?

Gravity wave amplitude > 0.1% above 35km

Radiosonde returns tend to end around 35km

- Balloons pop

(Lu et al. 2008)