Towards Poisson-limited photometry from ground-based telescopes

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Astronomical Photometry: Extinction Record

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

- Stebbins and Whitford (1945)

Astronomical Photometry: Stars as Standards

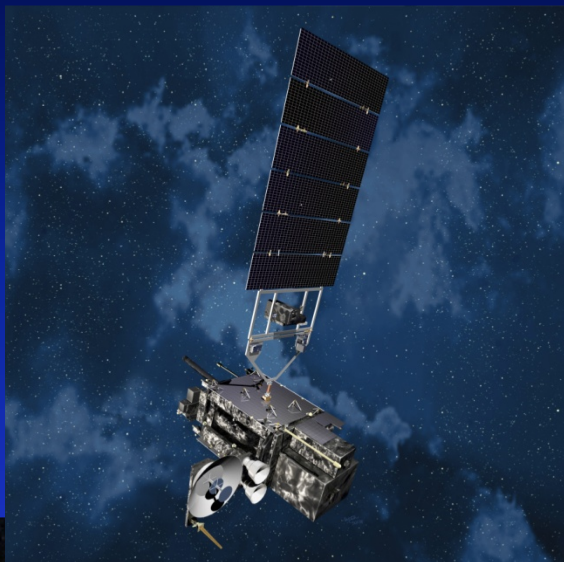
Stars: *Pros*

- shine for billions of years.
- are well known thermal sources.
- radiate from the UV to the IR.
- have understandable spectra.
- appear radiometrically stable over long time scales.
- are reasonably well distributed over the entire dome of the sky.
- are bright enough to be measured with small telescopes.
- are representative of the energy source of the Earth.

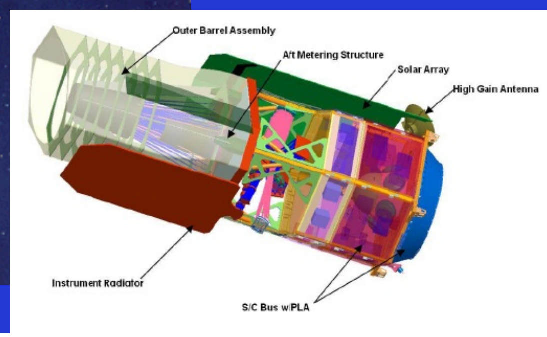
Stars: *Cons*

- can form as binary or multiple systems.
- can be luminosity variable.
- have apparent brightness dependent upon distance in a dusty, gas-filled spiral galaxy.
- have temperatures ranging from about 100,000 K to 2,500 K.
- have other stars nearby that limit photometric measurement.

Astronomical Photometry: Standard Stars



- All calibrated standard stars begin the calibration process using ground-based observations. Our set of stars can be used for:
  - calibrating Earth-observing spacecraft, including weather and climate observers,
  - calibrating ground- and space-based telescopes and optical NIR sensors,
  - SSA sensor test and calibration,
  - radiometric calibration of next-generation spectrophotometric detectors.



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)

Astronomical Photometry: Current State of the Art

Differential Photometry –

- Ratio of intensities of nearby objects in same field of view (FOV)
- Can achieve Poisson noise limit
- Typical precision of ~0.1%, heroic efforts ~0.01%

All-sky Photometry –

- Ratio of intensities of objects separated by many FOV
- Typical precision > 2%, heroic efforts ~1%

Absolute Photometry – 2% (heroic) for one star

Astronomical Photometry: Instrumental Limitations

Telescope Optics

- Field dependent illumination
- Dust accumulation
- Thermal expansion

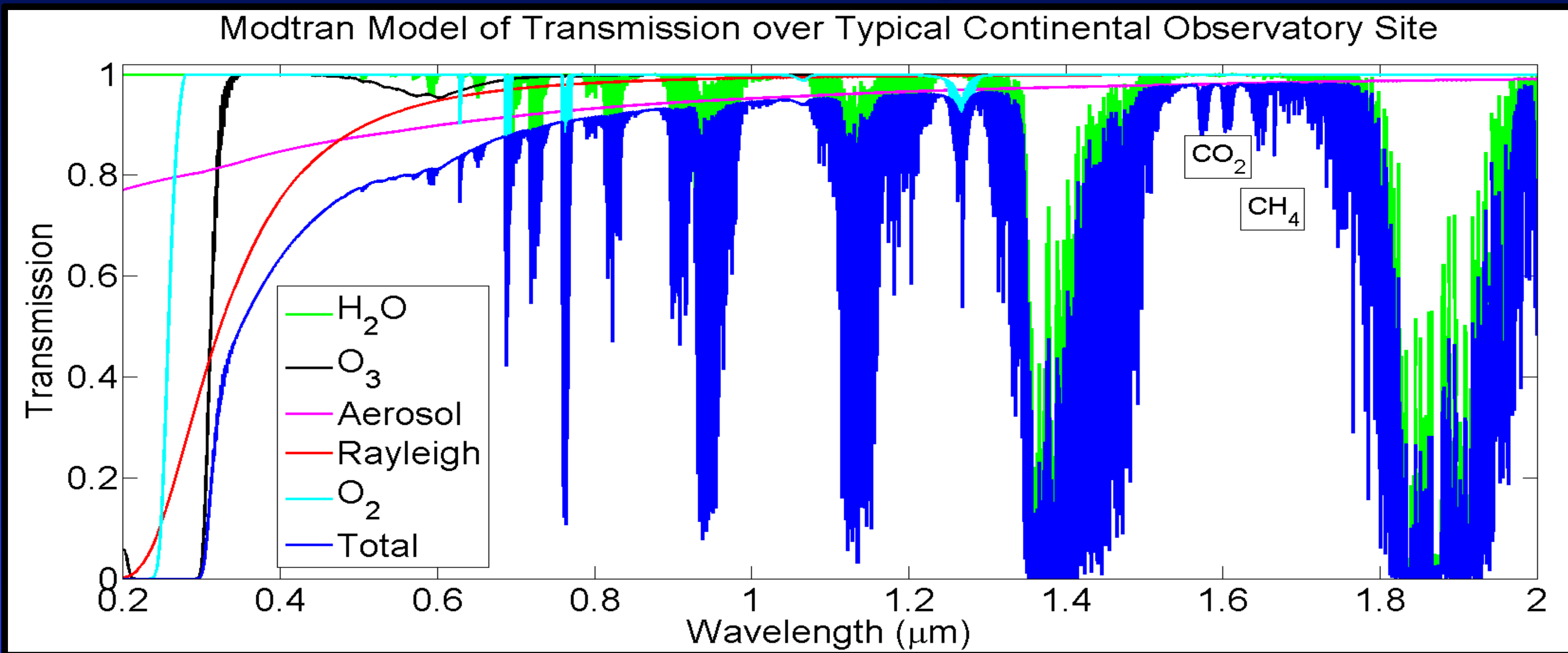
Filter Bandpass

- Deterioration
- Slight variations from telescope to telescope

Detector

- Pixel-to-pixel quantum efficiency variablility

Astronomical Photometry: Earth's Atmosphere



Molecular Scattering and Absorption

Aerosol Scattering and Absorption

Cloud Scattering

Atmospheric Extinction: Two Categories, Two Instruments

Slowly varying with wavelength

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

Instrumental Solution:

LIDAR

Rapidly varying with wavelength

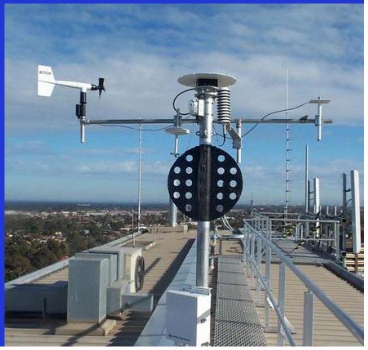
- H_2O absorption – significant temporal variability
- O_2 absorption – stable and easily modeled

Instrumental Solution:

Spectrophotometry of Absolute Standard Stars

Atmospheric Extinction: Additional Data

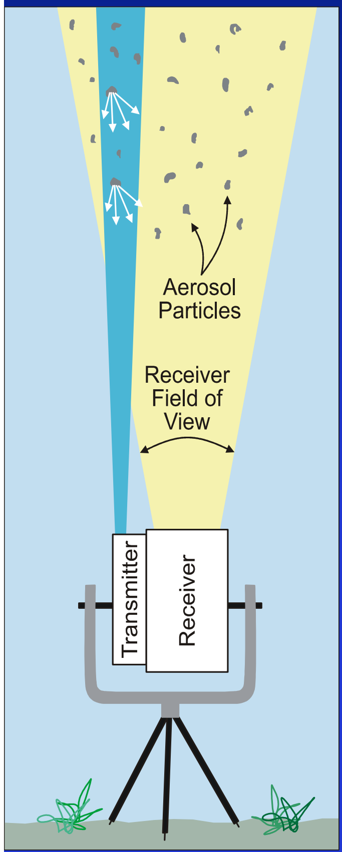
- Combine
  - Surface weather measurement
    - Rayleigh Scattering and O_2 absorption from pressure
    - AERONET aerosol data
  - Direct measurements of observed column
    - Direct Measurement – Radiosonde
    - PWV column from GPS
- As Input to Radiative Transfer Models
  - MODTRAN



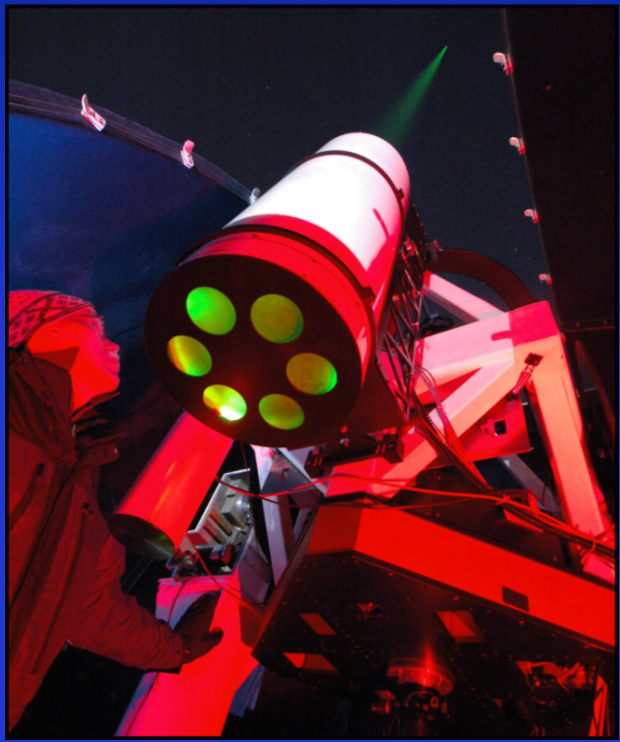
Measure the Atmosphere: LIDAR

LIght Detection and Ranging – laser analog to radar

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



- β_m ~ 10^{-5} per meter at sea level
  - Scales with density, h_0 ~8.4km
- Nγ ~ 10^{14} per pulse
- Return scales as e^{-h}/R^2
  - Dynamic range >10^9
    (from 100m to 60km)
- Time-gated return yields range



LIDAR:
The Astronomical Lidar for Extinction (ALE)

Prototype system for Observatory LIDAR

- Based on existing 0.67m telescope
- Transmitter:
  - 527nm, 70 μJ per pulse at 1500 Hz
  - Beam expanded to 300mm for eye safety
- 100mm short range receiver
- Photomultiplier Tubes
  - Analog voltage measurement below 10 km
  - Photon counting above 10 km

Design Goal – 10^6 photons per minute from above 20 km ASL at zenith

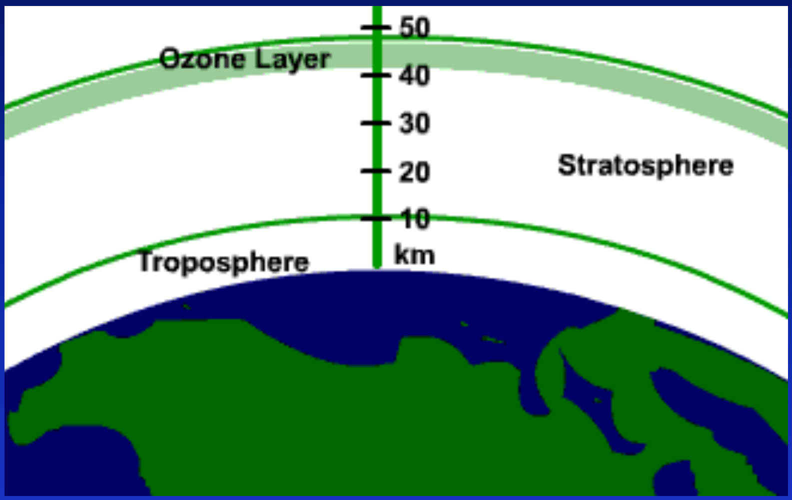
Photo by Dave Roberts, GTRI

ALE development was funded by NSF Grant 0421087.

LIDAR:
The Astronomical Lidar for Extinction (ALE)

The Big Idea

- Use the stable stratosphere as a quasi-constant scattering target
- Above 20 km, return is pure Rayleigh scatter *
- Density of scatterers measured by NWS radiosonde twice per day
- Extinction from atmosphere above 30 km is stable and small



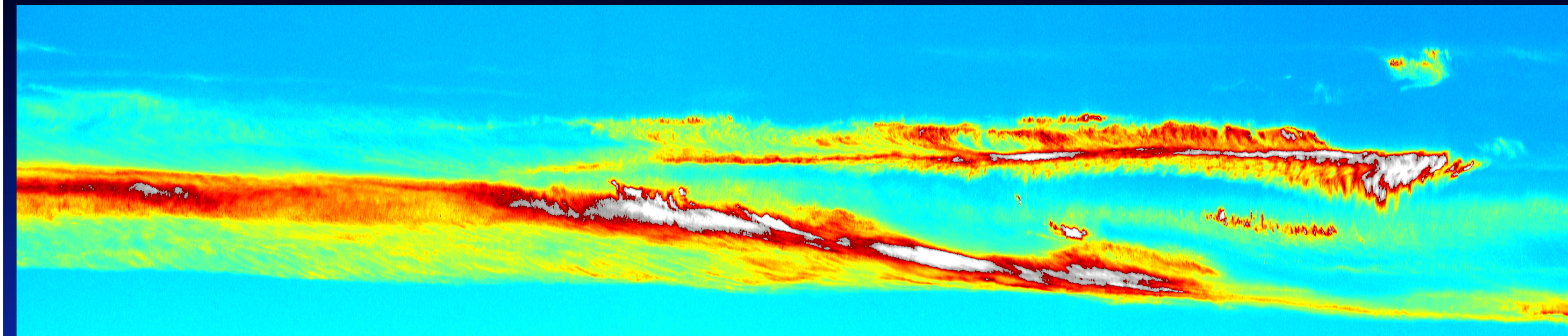
Under Construction:

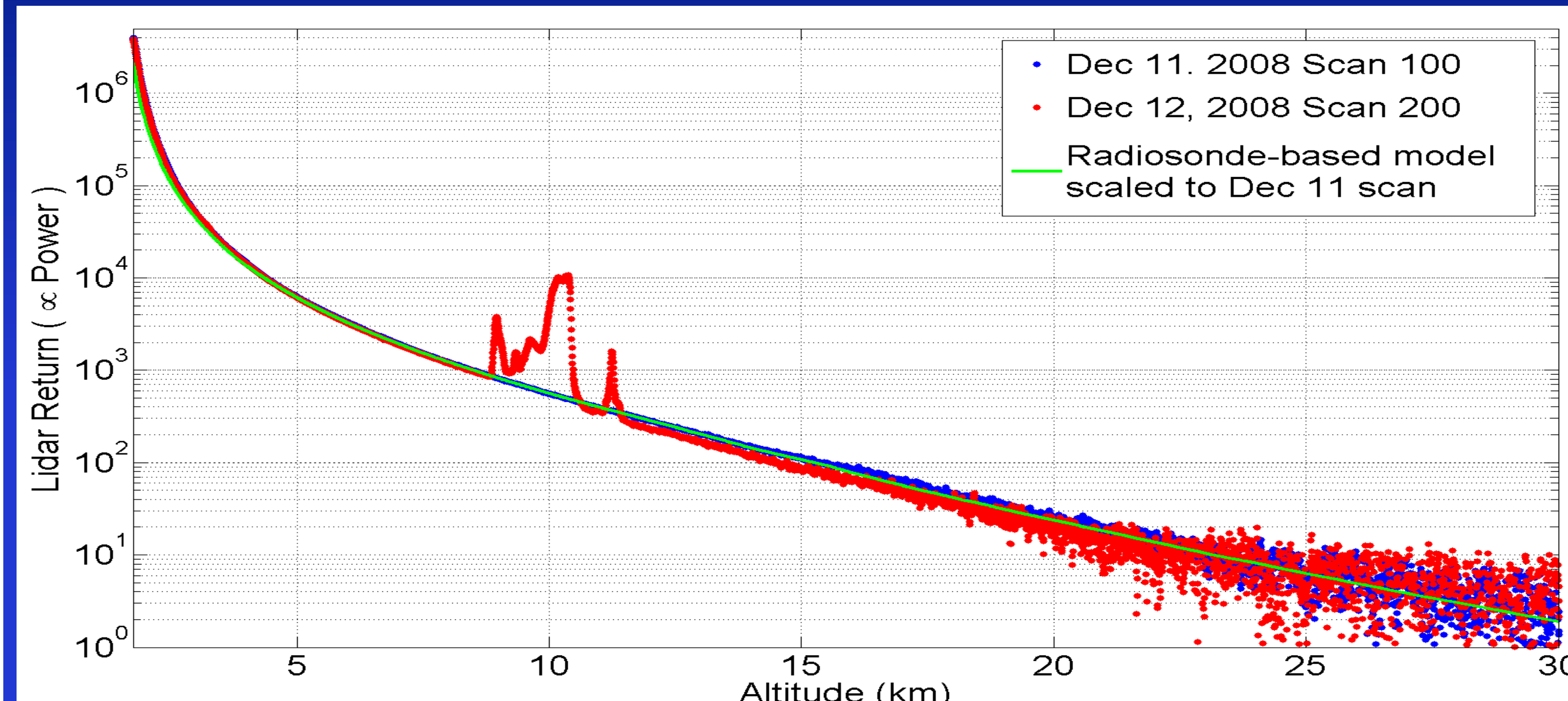
Multi-wavelength LIDAR with depolarization sensitivity

(1064 nm, 532 nm, 355 nm, 266 nm)

* →

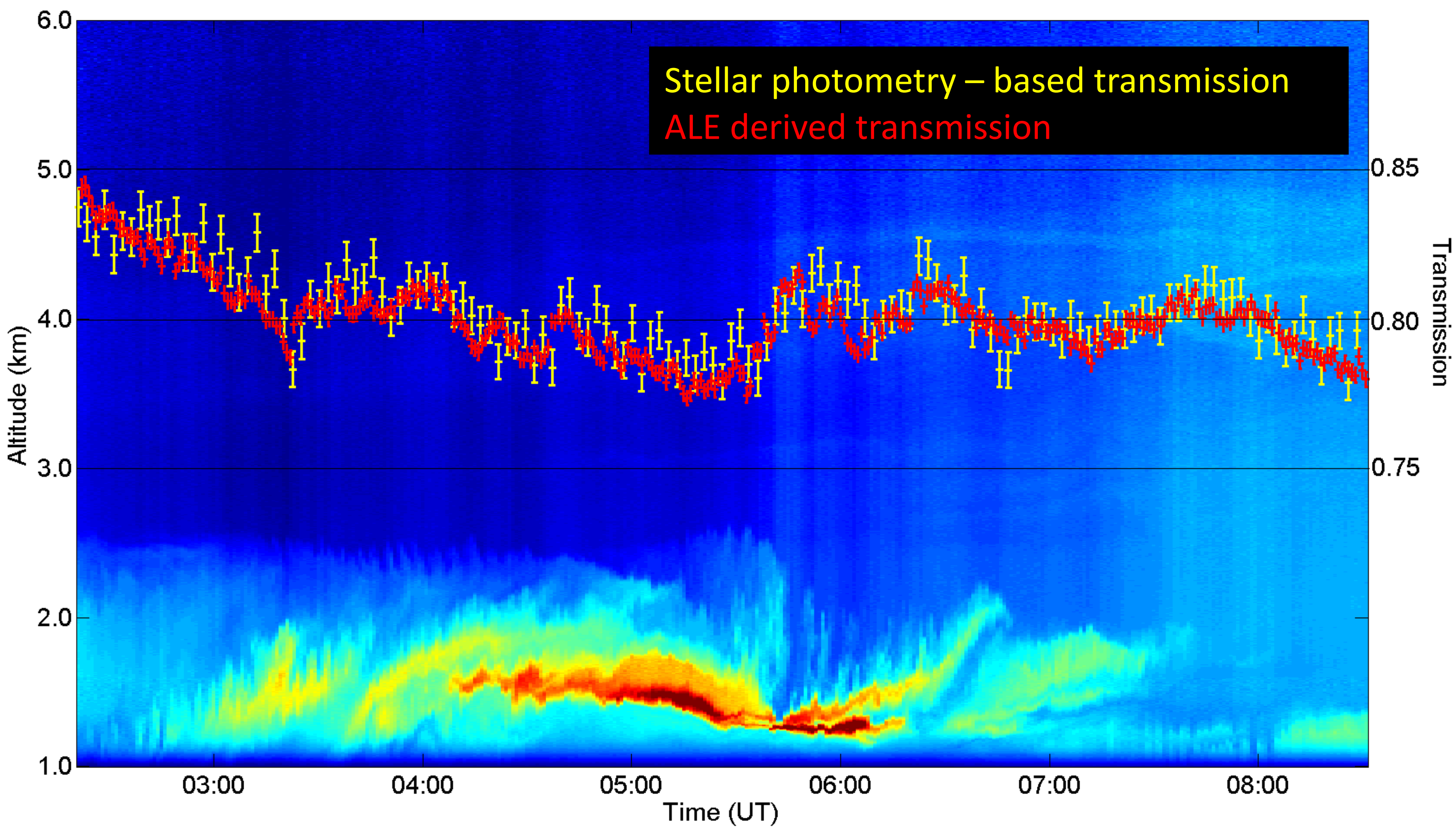
ALE





Dec 11. 2008 Scan 100
Dec 12, 2008 Scan 200
Radiosonde-based model scaled to Dec 11 scan
Lidar Return (∝ Power)
Altitude (km)

Measure the Atmosphere: ALE



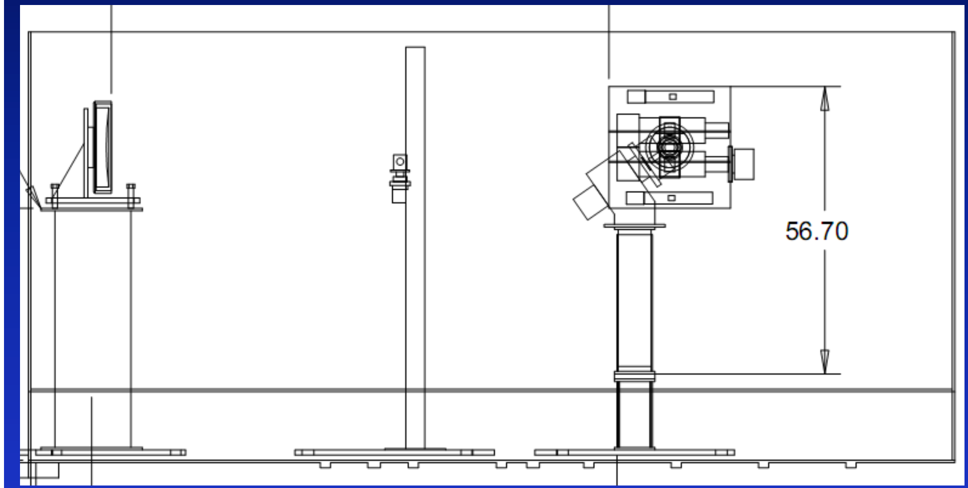
Astronomical Extinction Spectrophotometer (AESoP)

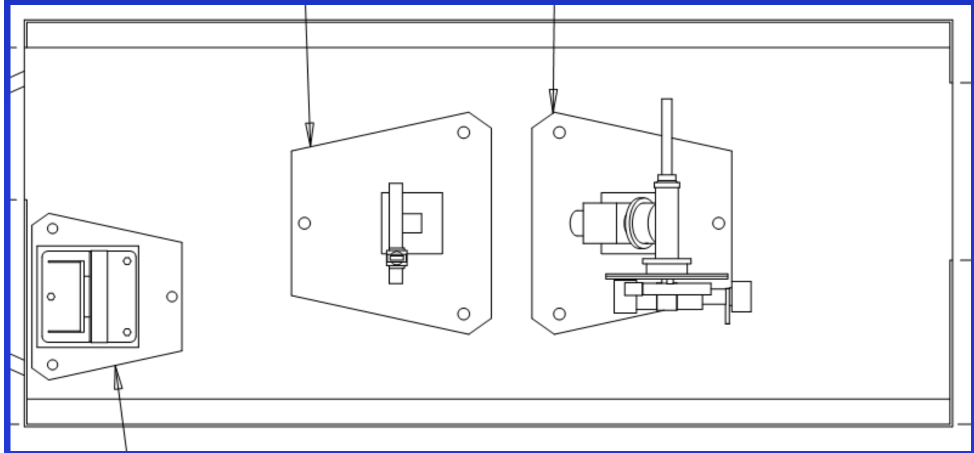
- AESoP Key Parameters
  - Free spectral range
    - Shortpass (2nd order): 320 nm– 550nm
    - Longpass: 550nm – 1050nm
  - Spectral resolution 0.6 nm, R = 1100 at 650nm
  - Pixel resolution 0.28nm at 650nm

- For bright stars, a large aperture is not required
- AESoP is based on 150 year old design
  - 105mm refractor
  - equatorially mounted
  - 90 lines/mm transmission grating mounted at the entrance aperture.
- No optical elements (other than an order separating filter) after the telescope objective lenses
- Photometric precision is fundamentally limited by scintillation.

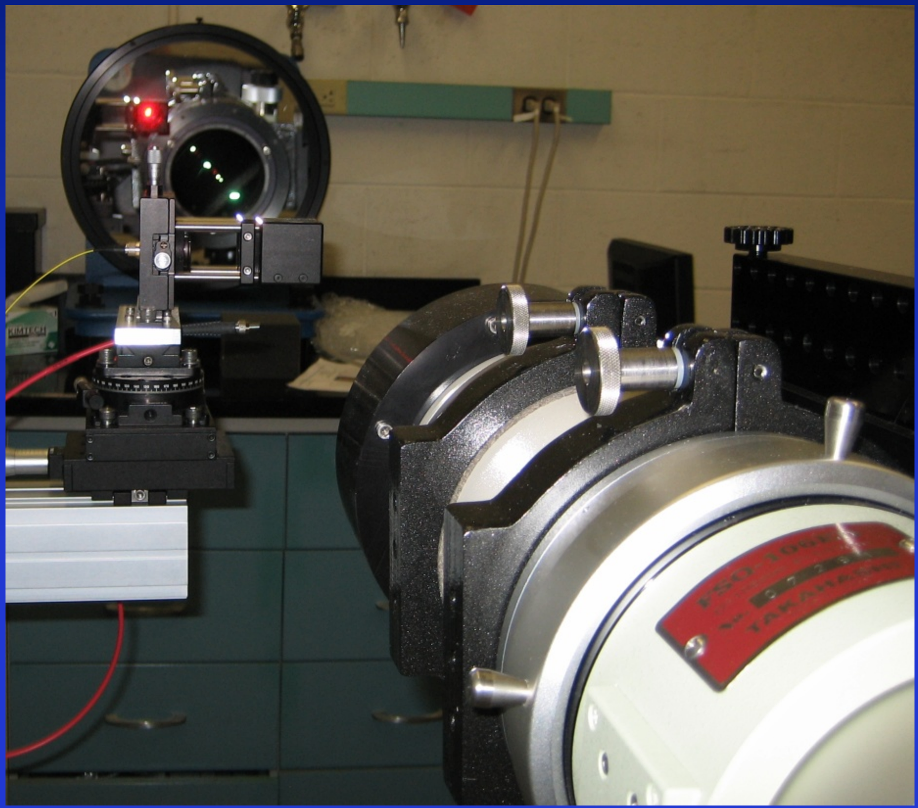
AESoP Calibration

Mobile Calibration Lab

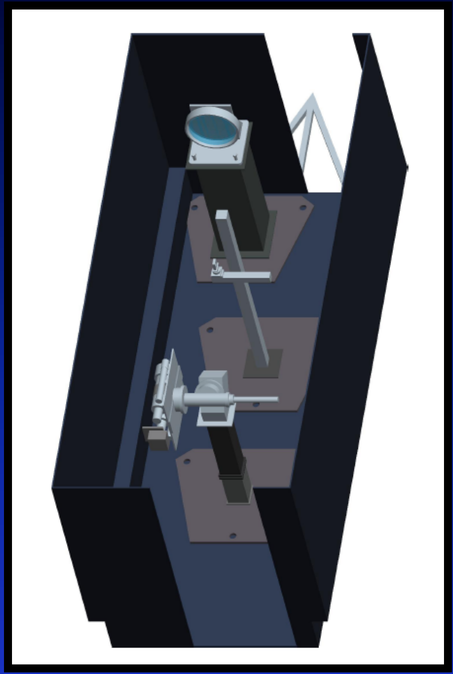




Current Test Configuration



AESoP Design Trade-Off



- Slitless Spectroscopy
  - The Good:
    - Spectrophotometric integrity – no light lost on slit edges
    - Sky emission lines not resolved
    - No diffraction from secondary spiders
    - Closed tube, near perfect baffling
  - The Bad:
    - Wavelength and pointing mixed in dispersion direction
      - Need for stable pointing/guiding, hence big mount
    - FOV not limited by slit -- source confusion
    - Fundamental resolution determined by image quality
      - But: AESoP designed so that resolution limited by pixel sampling in dispersion direction, not seeing

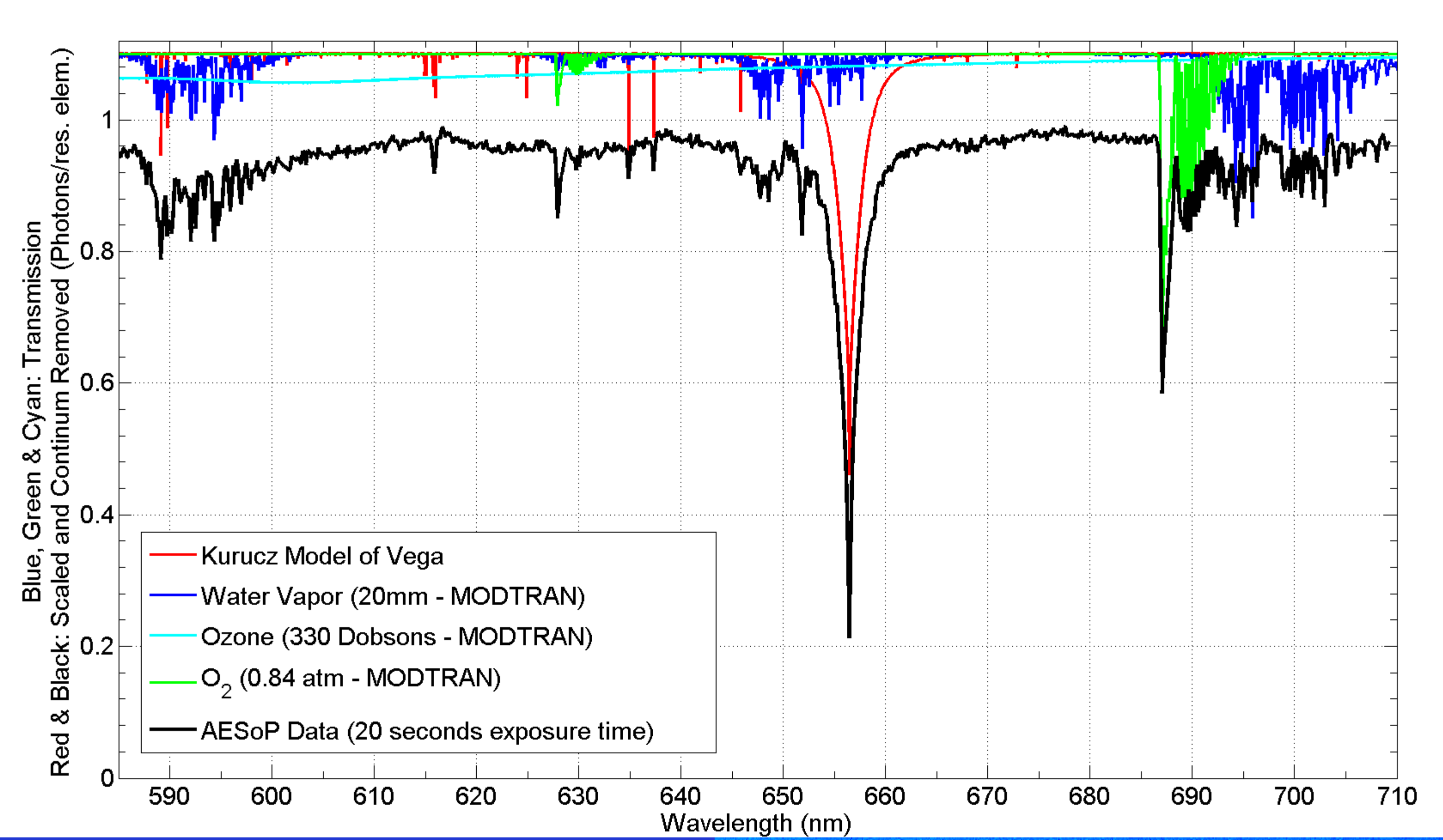
AESoP Operation

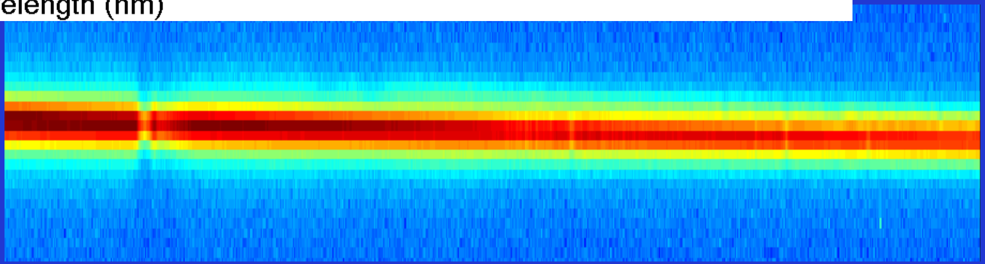
Fundamental technique the same as Hayes, Latham & Hayes (1975)

But:

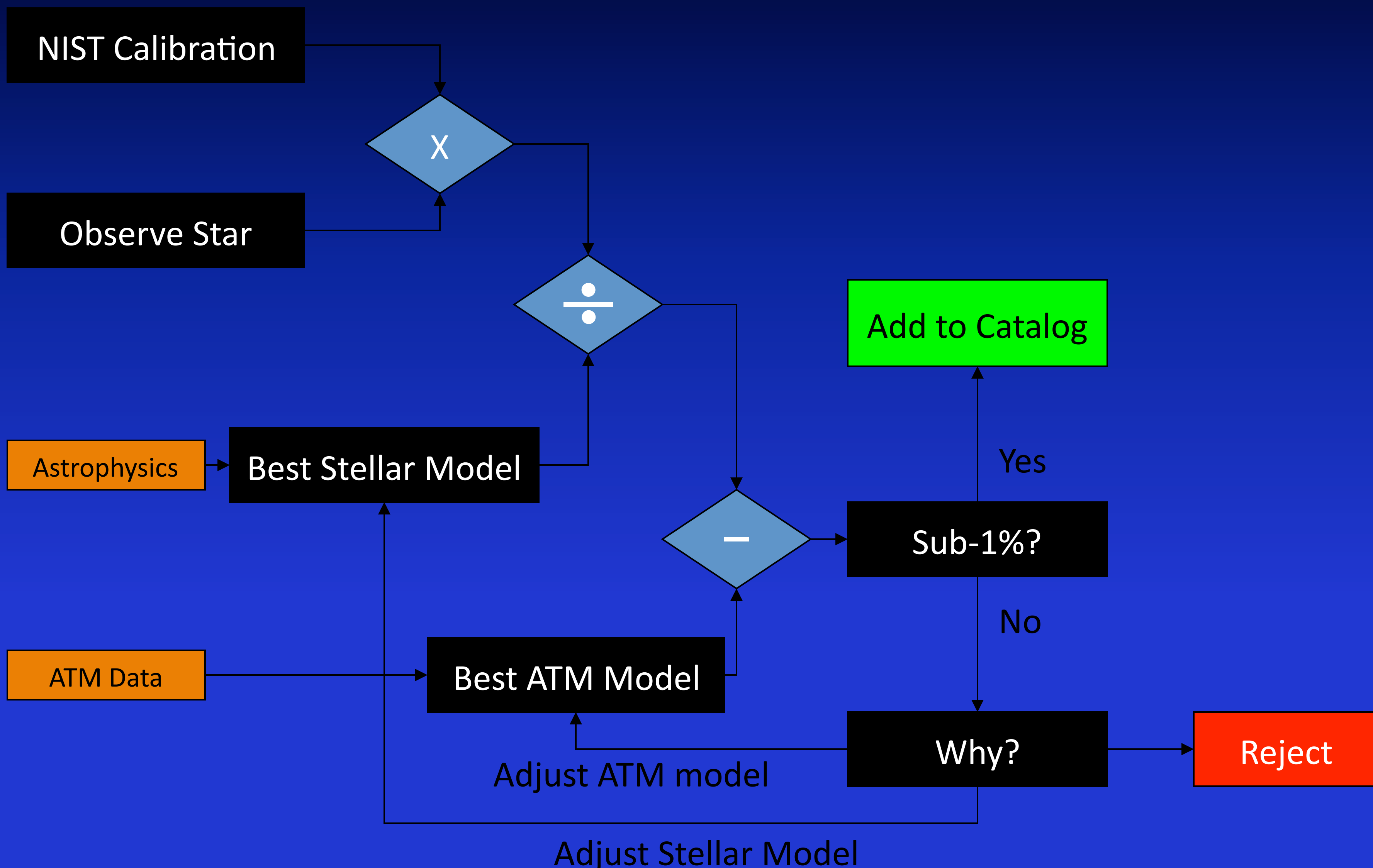
- Calibrations now detector-based instead of emitter-based
- Modern instrumentation
- Far more sophisticated radiative transfer models

AESoP Proof-of-Concept Data

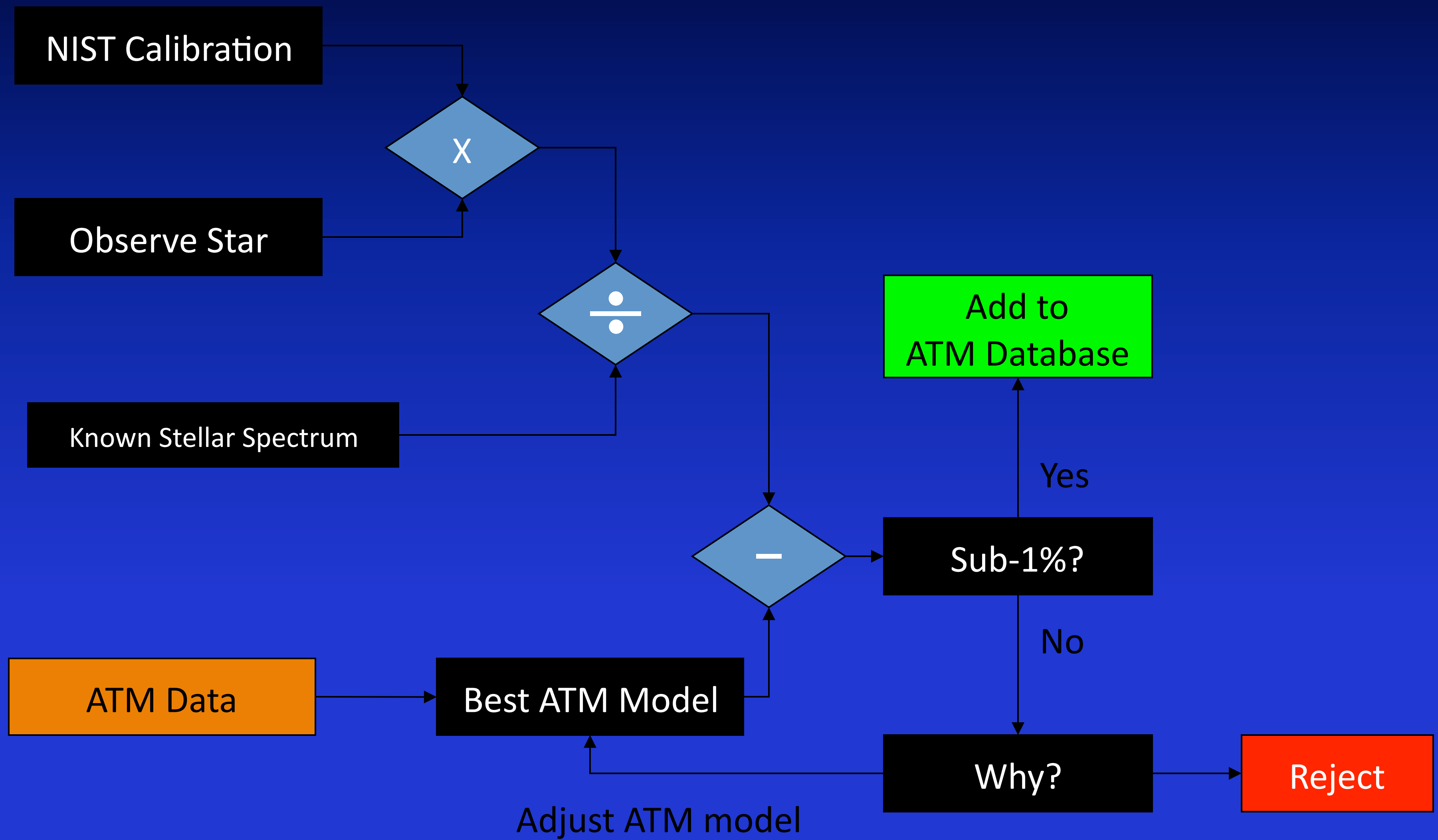




Making and Maintaining Absolute Standard Stars



Monitoring Transmission for Larger Science Telescope



Toward the Poisson Limit

We are attacking the primary sources of systematic error in ground-based photometry:

- Telescope throughput characterization under development by Harvard, NIST & PanSTARRS
  (Stubbs et al. 2010 astro-ph/1003.3465)
- Atmospheric transmission determination possible with deployable, affordable, automated systems
  - Dedicated instruments supporting larger telescopes
- Calibration of both to NIST standards