All-sky radiometric calibration of observed objects with known photon-limited uncertainties is the holy grail of astronomy and astrophysics.

The current largest identified source of systematic error impeding precise and accurate ground-based astrophysical radiometry is the transfer of light through Earth’s atmosphere.
Our Goal: Measurement Astrophysics

- Our goals with respect to Earth’s atmosphere:

1. Provide precise and accurate real-time extinction corrections to enable accurate astrophysical radiometry
   - Lidar: \(10^6\) photons in a minute from stratospheric backscatter
   - Spectroradiometry: NIST-traceable standard stars
   - Cameras: Wide FOV cameras for angular extinction mapping/checking

2. Demonstrate facility class instruments (with cost \(\sim\) 10% that of an AO system) that measure extinction in support of major telescopes, entire observatories, ground-based on-orbit calibration, and more

3. Use this instrument suite to help create the next generation of NIST-traceable radiometric standard stars

Our canonically stated goal is to provide “sub-1%” calibration of stars per 1nm resolution element from 350 – 1050 nm
What we produce, and why!

What is the transmission right now where we want to observe?

- The product of the instrument suite we are building and testing is an atmospheric transmission metadata stream, with its measurement errors, containing at **one minute cadence**:
  - Multiple (1 - 3 \( \lambda \)) calibrated lidar measurements of transmission
  - Spectroradiometry of a NIST-traceable standard star(s) in the field
  - Local (e.g. atmospheric pressure, temperature, etc.) and remote (e.g. satellite ozone measurements) weather and atmospheric data
  - Best fit MODTRAN model of the atmosphere informed by weather and spectroradiometric data
  - **Atmospheric transmission from 350nm to 1050nm at 1nm resolution**
Wavelength dependent transmission provided by the Astronomical Extinction Spectrophotometer (AESoP)

AESoP, a NIST-calibrated 100 mm diameter objective spectrophotometer, measures atmospheric extinction with one minute cadence at 0.6 nm resolution from 350 – 550 nm (2\textsuperscript{nd} order) and 550 – 1050 nm (1\textsuperscript{st} order). R = 1100 and pixel resolution $= 0.28$ nm at 650 nm.
The Astronomical Lidar for Extinction (ALE)

- Our first experiment: ALE measures the transmission of Earth’s atmosphere at 527nm to 0.25% precision per airmass every minute of time.
- Elastic backscatter lidar – not Raman or HSRL for time resolution and cost reasons
- The Facility Lidar Atmospheric Monitor of Extinction (FLAME) is on the way – three wavelengths

ALE is an eye-safe micropulse lidar on an alt-az mount with a 315mm transmitter, a 100mm short-range receiver and a 670mm long-range receiver providing 15m resolution to 30km range. 79 μJ pulses at 1500 Hz provides 120 mW system with photon counting detection.
ALE returns show that classical atmospheric extinction corrections can introduce systematic error.

The upper panel shows an ALE zenith time-height diagram for 18 April 2008 acquired by averaging lidar returns in one minute of time bins over an interval of 1.5 hours. The returns are expressed as the fractional difference \((data - model)/model\), where the model is a standard atmosphere plus an exponential aerosol. The black trace shows the relative transmission which is replicated in the lower panel with one minute, 0.2% single measurement standard deviations shown. Fifteen minute means with the standard deviation of the mean are shown with black error bars. These data derive from a clear night that would have been used for astronomy.

Transparency changes are due to changing aerosol distributions.
Absolute transmission derived from stratospheric Rayleigh return

- Measure Rayleigh scattering from the highly stable stratosphere
- Reference to sonde density profiles made every 12 hours at 0 and 12 hours Zulu.
Target the Stratosphere

- Troposphere
- Stratosphere
- Mesosphere

Weather

Volcanic Aerosols

Gravity Waves (Brunt-Vaisala, not Einstein)
The Stable Stratosphere

2011 sonde pressure measurements

December 2011 pressure measurements

ABQ differential density measurements

Southern Great Plains – ABQ density differences
Ongoing research: The stratosphere as a Rayleigh screen

Sonde measurements show the stratosphere from 20 km to 35 km to be very stable. Density over a month interval is shown to vary by less than the errors derived from sonde sensors.

There may be aerosols in the stratosphere. If stratified, lidar will resolve them. If mixed, we are investigating the diagnostic capability of multi-wavelength lidar. CALIPSO, HRSL and other measurements will provide additional data – perhaps the next systematic effect we must obviate.
For our techniques the gradient of transmission change is as important as the value of the transmission. The effect is that, in general, the lidar will not be spatially close enough to the target and will provide the wrong correction. If the clouds are stationary we try to measure an angular gradient (ACE, IR Cam). If the clouds move and/or form/dissipate it is the time rate of change integrated over a measurement timescale. Taylor’s approximation may apply.

“The Moon – Bringer of Clouds*”

A 3.5° x 3.5° field with extinction illuminated – why we need WFOV OIR cameras

*with apologies to Gustav Holst
Building a cirrus deck: an ALE zenith time-height diagram

High altitude cirrus demonstrates high frequencies in transmission variation can exist.

Cirrus between 6 – 12 km, 0.7 sec time resolution, 3.25 hour duration
Comparison of ALE returns to differential photometry

Differential photometry is proven to produce high precision radiometry. This sequence of differential radiometry through a 30 nm wide filter centered at 530 nm and ALE measurements (527 nm) demonstrates that lidar can correct for atmospheric extinction as well or better than differential techniques. Uncorrected photometry is due to angular separation between target and lidar, NOT a failure of the transmission measurement!

TU UMi is a δ Scuti variable star

--- differential radiometry

--- ALE
Mantra

• To achieve our radiometric precision goal a nightly mean or all-sky extinction measure is insufficiently accurate.

• To attain high precision and accurate measurements of atmospheric throughput requires physically measuring the column of air through which the supported telescope observes.

• OM