Two New Instruments to Calibrate the Visible Sky

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Measuring Atmospheric Transmission

What we really want:

Stars with calibrated spectral energy distributions
  • A range of brightness
  • Wide range of wavelength coverage
  • All over the sky
  • In real units: Watts, Meters, Nanometers, etc.

In other words, absolute calibration of standard stars

Stellar and transmission calibration are intimately linked
Detector-based Instead of Emitter-based Standards
NIST Stars

Spectral irradiance calibration (W/m²/nm) of bright stars (V<6) to NIST standards

Initially dozens, ultimately ~100 objects

- Vega, Sirius, 109 Vir, 19 targets from NGSL
  (insert your favorite target here)

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

Biggest known obstacle: Atmospheric Tx
  – But: Making absolute standard stars and measuring transmission go hand-in-hand
Atmospheric Transmission: Two Categories, Two Instruments

Rapidly varying with wavelength
- H$_2$O absorption – significant temporal variability
- O$_2$ absorption – stable and easily modeled

Instrumental Solution:
Calibrated Spectrophotometry

Slowly varying with wavelength
- Clouds – rapid temporal and angular variability
- Aerosols – confusion with O$_3$ absorption

Measurement Solution:
Calibrated LIDAR
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 mm²
- 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
- Easily removable from mount
- Calibrated at NIST
CAL Calibration in NIST TCF

Working Standard Photodiode
- Known responsivity (A/W)
- Known Amplifier transimpedance gain (V/A)
- Blue + are measure voltage
- Red line is model fit
  - Signal, rise time, offset and start time

CAL Data
- CCD read out at 50 rows/s
- Binned 20 x 1 along rows
- Each row records signal integrated over pupil
- Measured NEP: 11 aW/√Hz at 550nm
- Blue dots are measured count
- Red line is geometrical model fit
AESoP Instrument Checkout

- ~50 HeNe plasma lines matched over first order spectrum
- Dispersion is linear to < 0.03nm rms
AESoP Instrument Checkout

- Average of 100 – 10s exposures of 632nm normalized by average of 100 – 0.5s unsaturated exposures taken through 633/2 nm narrowband filter
First light on Vega (uncalibrated) June 14, 2012 – 1 second exposure through 520nm longpass filter
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Measure the Atmosphere: LIDAR

Light Detection and Ranging – laser analog to radar

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

- \( \beta_m \sim 10^{-5} \) per meter at sea level
  - Scales with density, \( h_0 \sim 8.4 \)km
- \( N_\gamma \sim 10^{14} \) per pulse
- Return scales as \( e^{-h/R^2} \)
  - Dynamic range >10^9
    (from 100m to 60km)
- Time-gated return yields range
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 0.5m long range receiver.

Long range photons split with dichroics and sent to individual photomultipliers.

DESIGN GOAL: $> 1 \times 10^6$ photons/minute from above 30km.
Calibrating FLAME

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

\[ N_\gamma (r) = \frac{N_0 \eta A}{2r^2} \left[ \frac{3}{8\pi} \beta_M (r) + \frac{P_\pi (r)}{4\pi} \beta_S (r) \right] T(r)^2 \]
Making and Maintaining Absolute Standard Stars

Observe Star

Irradiance Calibration

Best Stellar SED

Best ATM Model

Add to Catalog

Sub-1%?

Yes

No

Why?

Reject

Astrophysics

ATM Data

LIDAR

Adjust ATM model

Adjust Stellar SED
Monitoring Transmission for Other Science Telescope

NIST Calibration

Observe Star

Known Stellar Spectrum

ATM Data

Best ATM Model

Add to ATM Database

Sub-1%?

Why?

Reject

Adjust ATM model

Yes

No

Why?
Summary

- Bright stars absolutely calibrated to NIST spectral irradiance (W/m²/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 fall 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