Measuring NIR Extinction with GPS

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Water, Water Everywhere!

Typical Transmission: Apache Point Observatory
Water Absorption: Highly Variable

Two Echelle Spectra of an A Star
Same Airmass, 300% Change in Optical Depth
Fig. 8.— Mean values of 14,597 uncalibrated z-band flux measurements for the Stripe 82 G5-F5 star sample binned as a function of PWV. As discussed in Section 6, $\Delta'_{zraw}$ is an estimate of the change in raw z-band flux after correction for extinction as measured simultaneously in r band. The dashed line is based on the same theoretical calculations shown in Figure 6.

The changes in total absorption in z-band with PWV are significant, up to several percent, but these are largely removed via relative calibration techniques, with residuals that depend on SED. Statistical errors on the means are smaller than the points.

Change in Uncalibrated Flux: Repeat SDSS z Band Observations of F Stars

PWV = Precipitable Water Vapor
Differential Photometry

Detected Photons =

\[ \int \text{Earth Atmosphere} \times \text{Filter} \times \text{Detector} \times \text{Source SED} \times \text{Telescope} \ d\lambda \]

\[ \int \text{Star A} \times d\lambda \sim \text{Constant} \]

\[ \int \text{Star B} \times d\lambda \]

**Assumptions**
1. Contemporaneous observations of both stars
2. Perfectly calibrated 2D detector
3. Small angular separation between stars
4. Stellar SEDs same across filter bandpass

*mmag* Ground-based
Differential Photometry
Possible (Even in z Band)
Differential Photometry of Cool Stars

M Star 700-900nm (i+z) M Star

A Star 700-900nm (i+z) A Star

Low PWV ≠ High PWV

Up to 1% Effect in Differential Photometry of Cool Stars
Precise Telluric Models Can Help
Global Positioning System

Satellites have synchronized atomic clocks

“At the beep, the time will be exactly...”

Satellite positions precisely known

1.2 & 1.6 GHz

GPS measures light travel time: satellites to receiver

If Speed of Light (Index of Refraction) is Known:
Signals From Four Satellites Get You:
- Absolute X,Y,Z Position of Receiver
- Time Offset Between Receiver Clock and Satellite Clocks
GPS Timing Delays (Fixed Receiver)

Ionospheric Delay: 10 m +/- 1 mm

Frequency Dependent: Precisely Measured Using Dual Frequency GPS Data

“Dry Air”: 2 m +/- 1 mm

“Hydrostatic Delay”

Water Vapor: 0.03 to 0.3 m

“Wet Delay”

Many Sources of Error Eliminated By “Double Differencing” - Network of GPS

“Pseudo Range” 10m = 3 ns Timing Delay
Measurements: GPS, Temperature, Pressure

Dry Delay = \((2.2779 \pm 0.0024)P / F(Lat, Alt)\) (mm)

Barometric Pressure +/− 0.3 mbar
Function of Position on Earth (constant)

Wet Delay = Total Delay - (Ionospheric Delay + Dry Delay)

PWV \(\propto F(T) \times\) Wet Delay

Relative PWV +/− < 0.2 mm

Caveat: These are Estimated Zenith Quantities Azimuthal Symmetry Assumed

References: Bevis et al. 1992, 1994

Calculated From Raw GPS Data
Commercial Software (e.g. Bernese)
GPS Monitoring Networks
Suominet Network

http://www.suominet.ucar.edu/

Ware et al. 2000
PWV Monitor at Apache Point

Data Processed in Real Time by Suominet Project
PWV Estimates Every 30 Minutes

Lots of Great Work on Astronomical Applications of PWV Monitors:
Water Vapor: Highly Variable

PWV at Apache Point Observatory

3.5m Telescope Collecting Data

All Measurements
Water Vapor: Highly Variable

Histogram of Change in PWV Over 30 min Intervals
Two Years of “Good” Observing Conditions at APO
Fig. 2.— Two examples of theoretical telluric H$_2$O templates (solid lines) fit to ARCES A star observations (small points). These spectra highlight the strong impact changes in the total H$_2$O column have on the telluric absorption. In both cases, the residuals of the fits are excellent, having scatter $<2\%$.

ARCES on 3.5m at APO
100 Observations Over 1 Year, $R=30,000$  $S/N\sim150$
Forward Modeling of Spectra

Theoretical Telluric Templates
Custom Line-by-Line Radiative Transfer Code:

Fitting Telluric Templates to A Star Spectra
Free Parameters:
   Pixel-to-Wavelength Solution
   Spectrograph Line Spread Function
   Relative Water Vapor Optical Depth ($\tau$)
Forward Modeling

Fit RMS Typically 1% for Unsaturated Lines
GPS-based PWV vs. Observed Line Depths

Strong Correlation Between Best-fit Scale Factor and PWV Also Depends on Airmass

Blake & Shaw, 2011, PASP, 123, 1302
Applications

Precise Telluric Models:

Correcting NIR Photometry:

No Free Parameters
Match Observed (Unsaturated) Lines to ~1%
NIR Radial Velocity Measurements

Telluric Lines as a Simultaneous Absorption Reference
Fig. 6.— Top panel shows mean colors of 6,177 mid-M stars binned as a function of PWV. Here, $\Delta (r-z)$ is the difference in the measured color of a star relative to the stellar locus in (r-i) vs. (r-z) space. The dashed line is the result of a theoretical prediction that takes into account telluric H$_2$O absorptions following Equation 8, the SDSS filter bands, and synthetic stellar spectra from Brott & Hauschildt (2005). The theoretical (r-z) color difference is calculated between a mid-M star and a mid-G star reference, which should be representative of the average SED of all the bright stars in SDSS. Error bars are the formal statistical error on the mean of each bin and the null hypothesis of $\Delta (r-z) = 0$ is ruled out at >99% confidence. Bottom panel shows results of a consistency check were an empirical $\Delta (r-z)$ vs. PWV correction is calculated from the mid-M stars and then this correction is applied to the other half of the observations. After correction, the data are consistent with $\Delta (r-z) = 0$ ($P(\chi^2) = 0.73$).

Points: Calibrated r-z Colors of SDSS M Dwarfs Relative to Stellar Locus

Dashed Line: Estimate of PWV Bias
Assumes SDSS Photometric Solutions Based on an F star
Fig. 7.— Mean differential z-band magnitude, $\Delta z$, binned as a function of PWV for objects in Stripe 82 that were repeatedly observed by SDSS. The dashed lines are based on the theoretical calculations shown in Figure 6, again assuming a mid-G star as the reference SED. Formal statistical errors on the means are smaller than the points. 14,597 observations of 983 stars are included in the top panel and 25,005 observations of 1,553 stars in the bottom panel.
Conclusions

GPS-based PWV Estimates are Useful for Astronomy!

These Measurements Can Be Used to Generate Excellent Telluric Templates

These Templates Have Many Uses:
Correct Relative Photometry of Cool Stars
Radial Velocities and High-resolution NIR Spectroscopy

Future: A Network of Stations to Measure 3D Water Distribution in Real Time?
Fig. 3.— Two examples of theoretical telluric H$_2$O templates (solid lines) fit to ARCES A star observations (small points) in a spectral region with strong H$_2$O absorption, including saturated lines. Here we see evidence for significant residuals at the cores of some lines, as well as slowly varying residuals that we attribute in part to incomplete correction for fringing in the CCD detector.
Fig. 9.— Histograms of the expected variation in differential magnitude for a mid-M target and mid-G comparison star in different NIR bands given the PWV values at the times of all of the SDSS observations in our M star sample. The standard deviations of these distributions are: $\sigma_{\Delta z} = 0.003$, $\sigma_{\Delta i+z} = 0.004$, and $\sigma_{\Delta y} = 0.0003$ mag.