**pwv_kpno: A Python Package for Modeling the Atmospheric Transmission Function Due to Precipitable Water Vapor**

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**Abstract**

We present a Python package, \texttt{pwv_kpno}, which provides models for the atmospheric transmission due to precipitable water vapor (PWV) at user-specified sites. Using the package, ground-based photometric observations taken between 3000 and 12,000 Å can be corrected for atmospheric effects due to PWV. Atmospheric transmission in the optical and near-infrared is highly dependent on the PWV column density along the line of sight. By measuring the delay of dual-band GPS signals through the atmosphere, the SuomiNet project provides accurate PWV measurements for hundreds of locations around the world. The \texttt{pwv_kpno} package uses published SuomiNet data in conjunction with MODTRAN models to determine the modeled, time-dependent atmospheric transmission. A dual-band GPS system was installed at Kitt Peak National Observatory (KPNO) in the spring of 2015. Using measurements from this receiver we demonstrate that we can successfully predict the PWV at KPNO from nearby dual-band GPS stations on the surrounding desert floor. The \texttt{pwv_kpno} package can thus provide atmospheric transmission functions for observations taken before the KPNO receiver was installed. Using PWV measurements from the desert floor, we correctly model PWV absorption features present in spectra taken at KPNO. We also demonstrate how to configure the package for use at other observatories.

**Key words:** atmospheric effects – methods: observational – techniques: image processing

**Online material:** color figures

**1. Introduction**

Upcoming ground-based surveys, such as the Large Synoptic Survey Telescope, will require a photometric precision of one percent or better. Understanding and calibrating for the effects of atmospheric absorption is an important part of achieving this precision level (see Li et al. 2016; Burke et al. 2014, and Burke et al. 2010). Ground-based photometry redward of 5500 Å suffers from significant and variable opacity due to water vapor in the atmosphere. While ozone and aerosol scattering also play significant roles, their opacity is relatively smooth with wavelength. In contrast, the absorption due to precipitable water vapor (PWV) has a distinct and complex spectrum.

Astronomers traditionally calibrate broadband imaging by using a reference catalog to compute correction terms for color, airmass, and perhaps a higher-order, color-airmass term. This approach implicitly accounts for the effects of atmospheric opacity on observed images. In general, the color term accounts for the difference in filter and detector sensitivity with wavelength, but also includes some average contribution of the atmosphere above the telescope being used.

More detailed information can be obtained by observing a telluric standard star. These bright stars of known spectral energy distribution are well suited for determining the absorption and scattering of the atmosphere. In order to describe atmospheric effects, spectroscopy should be performed on a telluric standard at the same airmass as a desired target. This is ideally performed at the same position and time as the photometric observations. The total atmospheric absorption per wavelength can then be found by dividing the observed spectrum by tabulated results already corrected for absorption.

While this method is effective, the majority of telescopes are not configured to have an auxiliary spectrograph for observing telluric stars. Because atmospheric absorption is variable over time, observations of a standard star must be performed repeatedly and within a short time interval of other targets.
Even in setups with the capability to easily switch back and forth between mosaic imaging and single-object spectroscopy, such observations require diverting valuable observation time away from other targets.

As an alternative, astronomers commonly express the atmospheric absorption as a linear function of airmass. Using photometric observations taken over a range of airmass values, corrections are performed by fitting the linear function in each band. This approach assumes that the absorption scales linearly with airmass. However, the absorption spectrum of water is a complex series of very narrow absorption lines. These individual lines can saturate, and thus the absorption does not scale linearly with airmass. This non-linearity introduces errors due to higher-order effects when calibrating photometric images (Blake & Shaw 2011).

In the redder range of CCD sensitivity ($5500 < \lambda < 12,000 \text{ Å}$), the atmospheric transmission function is dominated by absorption due to precipitable water vapor (PWV). The use of GPS to measure the localized, PWV column density is a recently emerged technology in astronomy and an accurate alternative to traditional methods (Dumont & Zabransky 2001).

Through the use of atmospheric modeling, these PWV measurements can be used to simulate the atmospheric transmission. The resulting transmission function can then be used to correct photometric observations of sources with known spectral energy distributions for atmospheric absorption.

Here we introduce `pwv_kpno` a Python package that provides models for the atmospheric transmission due to H$_2$O at user-specified sites. By using MODTRAN models (Berk et al. 2014) in conjunction with publicly available PWV measurements, `pwv_kpno` is able to return models for the atmospheric transmission between 3,000 and 12,000 Å. The package was beta tested at Kitt Peak National Observatory (KPNO) using a dual-band GPS system that was installed at the WIYN 3.5-m telescope in 2015. Thus, direct PWV measurements at Kitt Peak are available starting in early 2015, but by using measurements from stations on the surrounding desert floor, the package is capable of modeling the atmospheric transmission for years 2010 onward. The package also provides access to tabulated PWV measurements, along with easy to use utility functions for retrieving and processing newly published PWV data.

In Section 2 we discuss the use of PWV measurements as a tool for correcting photometric observations. In Section 3 we present the features and functionality of `pwv_kpno`, including how to access tabulated PWV measurements and the package’s modeling capabilities. Section 4 demonstrates how to model the atmosphere for a user-specified site other than Kitt Peak. In Section 5 we present a validation of the package as a tool for correcting ground-based observations. A demonstration of how

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**Figure 1.** The $r$, $i$, and $z$ band mosaic filters of Kitt Peak National Observatory (gray) compared against the MODTRAN modeled atmospheric transmission function due to precipitable water vapor (blue). Atmospheric transmission functions are shown for an airmass of one and a precipitable water vapor (PWV) column density of 1 mm (top), 15 mm (middle), and 30 mm (bottom). Note that absorption features do not scale linearly with PWV, and some saturate at relatively low column densities. (A color version of this figure is available in the online journal.)
Figure 2. SED of a blackbody at 8000 K (black) across the i-band (left) and z-band (right) ranges. Shown in gray, the modeled atmospheric absorption for a PWV column density of 15 mm is applied to the SED. This is compared with the blackbody SED scaled using the integrated absorption in each band in red. (A color version of this figure is available in the online journal.)

Figure 3. Correcting photometric observations using tabulated values of a standard star introduces residual error in the magnitudes of other stars with different spectral types. The residual error in z band photometric zero-point due to absorption by precipitable water vapor is shown for three black bodies at 3000 (M type), 6000 (G type), and 10,000 K (A type). Results are shown as a function of the color of the reference star used to calculate the zero-point. Error values are shown for a PWV column density of 5 (left) and 30 mm (right). (A color version of this figure is available in the online journal.)
to use the package to correct for atmospheric effects is presented in Section 6. Finally, we present our conclusions in Section 7.

2. Background

The atmospheric transmission between 5500 and 12,000 Å is dominated by absorption due to PWV (Figure 1). The strength of PWV absorption lines in observed spectra correlate strongly with measurements of localized PWV column density (Blake & Shaw 2011). This indicates that PWV measurements can be combined with atmospheric models to provide estimates of the atmospheric transmission at a given date and time. However, accomplishing this requires a source of accurate and readily accessible PWV measurements. Furthermore, as PWV levels can change by over 10% per hour, measurements must be available in close to real time.

By measuring the delay of dual-band GPS signals traveling through the atmosphere, it is possible to determine the PWV column density along the line of sight (see Braun & Van Hove 2005; Dumont & Zabransky 2001, and Nahmias & Zabransky 2004). This approach is made even more appealing by the existence of several established GPS networks dedicated to the measurement of geological and meteorological data on the international scale. The SuomiNet project7 (Ware et al. 2000) is a meteorological initiative that uses data from multiple GPS networks to provide semi-hourly PWV measurements. It currently publishes meteorological data from hundreds of receivers throughout the United States and Central America.

2.1. Effects of PWV on Photometric Calibration

When correcting photometric observations for atmospheric effects, astronomers commonly express atmospheric absorption as a linear function of airmass. In this approach photometric observations are corrected by fitting for a set of extinction coefficients $k'$ and $k''$ in each band. For example, given an airmass $X$, the observed $i$ and $z$ band magnitudes of a standard star are related to the tabulated, intrinsic magnitudes $z_0$ and $i_0$ by a set of linear equations:

$$z = z_0 + k'_z \cdot X + k''_z (b - v) \cdot X,$$

$$i = i_0 + k'_i \cdot X + k''_i (b - v) \cdot X.$$  

The first-order extinction term $k'$ accounts for the decrease in a star’s observed flux with airmass. The inclusion of a second-order coefficient $k''$ accounts for the fact that the observed flux of blue stars decreases faster than red stars as they approach the horizon.

To measure the second-order extinction, observations are taken of a red and blue star over a wide airmass range. The

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7 For more information, see https://www.suominet.ucar.edu.
second-order extinction in each band can then be found by fitting for the difference in magnitude between the two stars:

\[ \Delta z = k''_z \Delta (b - v) \cdot X + \Delta z_0, \]
\[ \Delta i = k''_i \Delta (b - v) \cdot X + \Delta i_0. \]

Using the resulting value for \( k'' \), the first-order extinction coefficient is then found by fitting Equations (1) and (2). Although this method does account for a first-order airmass dependence, it does not directly account for any nonlinear effects. This is to say it does not account for parts of the atmospheric transmission having a nonlinear airmass dependence.

For a PWV column density at zenith \( PWV_z \), the column density along the line of sight is given by

\[ PWV_{\text{los}} = PWV_z \cdot X. \]

However, due to saturation, not all absorption features scale linearly with PWV concentration: some features saturate at relatively low concentrations (<10 mm). Thus, a linear function of airmass and color is not sufficient to describe the atmospheric transmission from PWV.

Figure 2 details the error introduced by considering PWV absorption averaged over a bandpass versus the actual absorption spectrum. Because atmospheric absorption varies with wavelength, it affects stars differently depending on their spectral type. This means that variations in the spectral types of photometric standards used to correct an image introduce errors in the magnitudes of observed targets. This effect is more pronounced for higher airmass due to the increased PWV along the line of sight, and is an important consideration for KPNO where \( PWV_z \) exceeds 20 mm over 13% of the time.

Demonstrated in Figure 3, when using a type A star to correct cooler G or M type stars, spectral variations between stars used in the atmospheric correction can introduce errors as large as \(-0.02 \text{ mag}\). This error is particularly important when performing high accuracy photometry to 1% or better. An alternative is to correct photometric observations using atmospheric models.

For an atmospheric transmission, \( T(\lambda) \), the photometric correction for an object with a spectral energy distribution, \( S(\lambda) \), is given by

\[ C = \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S(\lambda) \cdot T(\lambda) \, d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S(\lambda) \, d\lambda}, \]

where the integration bounds are defined by the wavelength range of the photometric bandpass. Using atmospheric models,
Figure 6. Linear fits to measurements of precipitable water vapor (PWV) column density taken at four different locations vs. simultaneous measurements taken at Kitt Peak. Each row corresponds to a different location being compared against Kitt Peak, with measurements shown on the left and binned residuals shown on the right. The slope ($m$) and y-intercept ($b$) is shown for each fit. The correlation in PWV column density between different sites allows the PWV column density at Kitt Peak to be modeled using measurements from other locations.

(A color version of this figure is available in the online journal.)
measurements of the PWV column density are used to determine $T(\lambda)$ at a given date, time, and airmass. If tabulated values for $S(\lambda)$ are not available, spectral templates are used instead. For example, the SED of a star is well estimated by its color, due to the strong relationship between stellar spectral type and intrinsic color.

2.2. Use of GPS at Kitt Peak

In 2015 March, we installed SuomiNet connected weather station on top of the WIYN 3.5 meter telescope building at Kitt Peak National Observatory. In addition to a GPS receiver, the station includes barometric, temperature, and wind speed sensors. SuomiNet compiles measurements from its affiliated weather stations at thirty minute intervals. These semi-hourly measurements, in addition to the local PWV column density along zenith, are then released publicly on an hourly basis.

To prevent equipment damage, the weather station at Kitt Peak is powered down during lightning storms. This creates gaps in the available SuomiNet data for Kitt Peak. Additionally, the barometric sensor was malfunctioning in 2016 from January through March, so we ignore any SuomiNet data.
published for Kitt Peak during this time period. The sensor has since been repaired, but occasionally records a non-physical drop in pressure. We disregard these measurements by ignoring any meteorological measurements taken for Kitt Peak with a pressure below 775 mbar.

To determine the PWV level during periods without SuomiNet data, measurements from other nearby receivers can be used to model the PWV level at Kitt Peak. This model can also be used for times before the Kitt Peak receiver was installed. In addition to data taken at Kitt Peak, the \texttt{pwv\_kpno} package uses measurements from four other receivers within a 45 mile radius at varying levels of altitude. This includes receivers located at Amado (AMAZ), Sahuarita (P014), Tucson (SA46), and Sells (SA48), Arizona. The location of these receivers is shown in Figure 4(a), with SuomiNet measurements for Kitt Peak, Amado, and Sells shown in Figure 5.

Note that the PWV level at each location follows the same seasonal trend, but the PWV concentration at Kitt Peak tends to be lower. As each of the chosen receivers are geographically close together, variations in PWV between Kitt Peak and the four supplementary locations are predominantly caused by differences in altitude. Shown in Figure 6, the PWV level at each location can be related to the PWV level at Kitt Peak by applying a linear fit. Each fit is able to predict the PWV column density at Kitt Peak to a precision of 1 mm plus 10% of the predicted value.

For times when SuomiNet data is unavailable for Kitt Peak, each of the linear fits are used to estimate the PWV column density at Kitt Peak. The resulting estimations are then averaged and used to supplement data taken by the Kitt Peak weather station. This full data set provides a model for the PWV column density at zenith over time.

To determine the PWV column density for a specific date and time, \texttt{pwv\_kpno} first determines the concentration along zenith by interpolating from the supplemented PWV data. The PWV column density along the line of site is then calculated using Equation (5). Using this value, \texttt{pwv\_kpno} is able to determine the atmospheric transmission using a set of tabulated MODTRAN models.

3. Features and Use of \texttt{pwv\_kpno}

The \texttt{pwv\_kpno} package provides access to models for the atmospheric transmission due to PWV at any location within the SuomiNet GPS network. However, the package is configured by default to return models for Kitt Peak National Observatory. We here demonstrate the features of \texttt{pwv\_kpno} using the default model for Kitt Peak and further discuss modeling custom sites in Section 4.

\texttt{pwv\_kpno} is registered with the Python Package Index and is compatible with both Python 2.7 and 3.5 through 3.7. Using PWV measurements published by the SuomiNet project, the package is able to determine the atmospheric transmission between 3000 and 12,000 Å. The package also provides methods for the automated retrieval and processing of published SuomiNet data.

3.1. Accessing PWV Data

To model the atmospheric transmission for a given date and time, \texttt{pwv\_kpno} requires there to be SuomiNet data stored on the user’s local machine. Each package release contains the necessary data to return models for Kitt Peak from 2010 through the end of the previous year. This data is automatically included when installing the package.

Access to tabulated PWV data and modeling of the PWV transmission function is provided by the \texttt{pwv\_atm} module. A list of years that have been downloaded from SuomiNet to the user’s local machine can be retrieved using the \texttt{downloaded\_years} method:

\begin{verbatim}
>>> from pwv\_kpno import pwv\_atm
>>> pwv\_atm\downloaded\_years()
[2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017]
\end{verbatim}

The returned list includes all years for which any amount of data has been downloaded.

To update the locally stored data, \texttt{pwv\_kpno} can be used to automatically retrieve and processes new data from SuomiNet. This is achieved using the \texttt{update\_models} method:

\begin{verbatim}
>>> pwv\_atm\update\_models()
[2017, 2018]
\end{verbatim}

Here, the returned list includes any years for which new data was downloaded. By default, the function will download all published data for any years not currently present on the local machine. In addition, it will also download data for the most recent year that is locally available. This method ensures there are no years with incomplete measurements in the locally available data. If desired, the user can alternatively specify a specific year to download from 2010 onward.

In addition to downloading data for Kitt Peak, the \texttt{update\_models} method also downloads measurements taken at the four supplementary locations shown in Figure 4(a). Each time the method is run, a new set of linear fits is created to describe the PWV concentration at Kitt Peak as a function of the PWV concentration at each supplementary location. These new fits are then used to recreate the entire supplemented PWV model for Kitt Peak. The error in PWV modeled using each of these fits is taken as the standard deviation of that fit’s residuals.

Users can access the locally available SuomiNet data using the \texttt{measured\_pwv} method. Results are returned as an Astropy table (Astropy Collaboration et al. 2013) and can be independently filtered by year, month, day, and hour:
Excluding the date column, each column is labeled using the SuomiNet identification codes for the GPS receivers.

\texttt{pwv\_kpno} also provides access to the modeled PWV column density at Kitt peak via the \texttt{modeled\_pwv} method. As in the previous example, these results can also be filtered independently by year, month, day, and hour:

\begin{verbatim}
>>> year=2016, month=11, day=14

KITT Kitt\_err P014 ...
------------------------- ---- ------ ---- ...
2016-11-14 00:15 4.7 1.025 6.9 ...
2016-11-14 00:45 4.3 1.025 6.7 ...
2016-11-14 01:15 3.9 0.925 6.7 ...
... ... ...
\end{verbatim}

3.2. Modeling the Atmosphere

For a known PWV column density, the package provides access to the modeled atmospheric transmission via the \texttt{trans\_for\_pwv} function. This method returns the modeled transmission function as an Astropy table with wavelengths ranging from 3000 to 12,000 Å. For example, given a PWV column density of 13.5 mm:

\begin{verbatim}
>>> wavelength = np.arange(7000, 10000, 100)
>>> psd = atm.trans(temp, wavelength, pwv)
\end{verbatim}

Atmospheric models can also be accessed for a given datetime and airmass using the function \texttt{trans\_for\_date}:

\begin{verbatim}
>>> year=2013, month=12, day=15, hour=5, minute=35, tzinfo=pytz.utc

wavelength transmission transmission\_err
Angstrom
----------------- ------------- ---------------
3000.00 0.9999999916 1.7305648359e-08
3000.05 0.9999999916 1.7305648359e-08
3000.10 0.9999999916 1.7305648359e-08
... ...
\end{verbatim}

If \texttt{pwv\_kpno} does not have any supplemented SuomiNet data within a day of the requested datetime, an exception is raised. Both the \texttt{trans\_for\_pwv} and \texttt{trans\_for\_date} functions determine the atmospheric transmission by returning a set of MODTRAN transmission models.

### 3.3. Modeling a Blackbody

The \texttt{blackbody\_with\_atm} module provides functions for modeling the effects of PWV absorption on a blackbody SED. For example, consider a blackbody at 8000 K under the effects of atmospheric absorption due to 15 mm of PWV. For a given array of wavelengths in angstroms, the \texttt{sed} method returns the corresponding spectral energy distribution:

\begin{verbatim}
>>> from pwv\_kpno import blackbody\_with\_atm

sed = bb\_atm.sed(temp, wavelength, pwv)
\end{verbatim}

The SED from the above example can be seen in Figure 2. If desired, the SED of a blackbody without atmospheric effects can also be achieved by specifying a PWV column density of zero.

Using the \texttt{magnitude} function, users can determine the magnitude of a blackbody in a given band. For example, in the \texttt{i} band, which ranges from 7000 to 8500 Å, the AB magnitude of a blackbody is found by running

\begin{verbatim}
>>> band = (7000, 8500)
>>> mag = bb\_atm.magnitude(temp, band, pwv)
\end{verbatim}

Here, the \texttt{i} band is treated as a top-hat function, however, the \texttt{magnitude} function also accepts \texttt{band} as a two dimensional array specifying the wavelength and response function of a real-world band. As in the previous example, the magnitude of a blackbody without the effects of atmospheric absorption can be found by specifying a PWV level of zero.
4. Modeling Other Locations

By default, `pwv_kpno` provides models for the PWV transmission function at Kitt Peak National Observatory. However, `pwv_kpno` also provides atmospheric modeling for user customized locations. Modeling multiple locations is handled by the `package_settings` module, and allows modeling at any location with a SuomiNet connected GPS receiver.

Each site modeled by `pwv_kpno` is represented by a unique configuration file. Using the `ConfigBuilder` class, users can create customized configuration files for any SuomiNet site. As an example, we create a new model for the Cerro Tololo Inter-American Observatory (CTIO) near La Serena, Chile:

```python
>>> from pwv_kpno.package_settings import \
>>>     ConfigBuilder
>>> new_config = ConfigBuilder()
>>>     site_name="cerro_tololo",
>>>     primary_rec="CTIO",
>>>     sup_rec=[],
>>>     wavelength=custom_wavelengths,
>>>     cross_section=custom_cs)
>>> new_config.save_to_ecsv(\n>>>     './cerro_tololo.ecsv')
```

Here, `site_name` specifies a unique identifier for the site being modeled, `primary_rec` is the SuomiNet ID code for the GPS receiver located at the modeled site, and `sup_rec` is a list of SuomiNet ID codes for nearby receivers used to supplement measurements taken by the primary receiver. Unlike the default model for KPNO, there are no additional receivers near the CTIO and so `sup_rec` in this example is left empty (the default value). By default, `pwv_kpno` models use MODTRAN estimates for the wavelength dependent cross section of H2O from 3000 to 12,000 Å. The optional `wavelength` and `cross_section` arguments allow a user to customize these cross sections in units of Angstroms and cm\(^2\) respectively.

If desired, users can specify custom data cuts on SuomiNet data used by the package. Data cuts are defined using a 2d dictionary of boundary values. The first key specifies which receiver the data cuts apply to. The second key specifies what values to cut. Following SuomiNet’s naming convention, values that can be cut include PWV (“PWV”), the PWV error (“PWVerr”), surface pressure (“SrfcPress”), surface temperature (“SrfcTemp”), and relative humidity (“SrfcRH”). For example, if we wanted to ignore measurements taken between two dates, we can specify those dates as UTC timestamps and run

```python
>>> data_cuts = {'CTIO':
>>>     {'SrfcPress': [\n>>>         [time_start, time_end]
>>>     ]
>>> }
```

Once a configuration file has been created, it can be permanently added to the locally installed `pwv_kpno` package by running

```python
>>> from pwv_kpno.package_settings import \
>>>     settings
>>> >>> settings.import_site_config(\n>>>     './cerro_tololo.ecsv')
```

This command only needs to be run once, after which `pwv_kpno` will retain the new model on disk, even in between package updates. The package can then be configured to use the new model by running

```python
>>> settings.set_site("cerro_tololo")
```

After setting `pwv_kpno` to a model a specific site, the package will return atmospheric models and PWV data exclusively for that site. It is important to note that this setting is not persistent. When `pwv_kpno` is first imported into a new environment the package will always default to using the standard model for Kitt Peak, and the above command will have to be rerun.

A complete summary of package settings can be accessed using attributes of the `settings` object:

```python
>>> settings.set_site('kitt_peak')
>>> print(settings.site_name)
>>> print(settings.available_sites)
>>> print(settings.receivers)
>>> print(settings.primary_rec)
>>> print(settings.supplement_rec)
>>> settings.export_site_config(\n>>>     './current_site_name.ecsv')
```

5. Validation

From 2010 September 16 through September 20, an observation run was performed on 18 standard stars using the
6. Package Demonstration

The pwv_kpno package can be used to correct both spectrographic and photometric observations. As an example, we use the pwv_kpno package to determine the atmospheric correction presented in Figure 7. We also demonstrate how to calculate the photometric correction factor defined in Equation (6) for a blackbody.

6.1. Correcting Spectra

Spectrographic observations are corrected by dividing observed spectra by the modeled atmospheric transmission function. To account for the spectral resolution function of the observing spectrograph, the modeled transmission is first binned to approximately match the observed spectra’s resolution. Depending on the resolution of the observation, further smoothing can then be performed using a Gaussian kernel. Assume that the observed wavelength and flux values are stored in equal length arrays obs_wavelength and obs_flux, respectively. Using the date, time, and airmass of the observation, the binned transmission function is found by running

```python
>>> import numpy as np
>>> resolution = 16 # Angstroms
>>> bins = np.arange(
>>>     min(obs_wavelength),
>>>     max(obs_wavelength+1),
>>>     resolution)
>>> airmass = 1.2
>>> obs_data = datetime(2010, 09, 19, 6, 29)
>>> tz_info=pytz.utc)
>>> transm = pwv_atm.trans_for_date
>>>     (obs_date,
>>>     airmass,
>>>     bins)
```

To divide the observed spectrum and modeled transmission, we linearly interpolate the binned transmission to the observed wavelength values. We then apply a Gaussian smoothing using an arbitrary standard deviation of 2 Å:

```python
>>> from scipy.ndimage.filters import Gaussian_filter
>>> interp_transm = np.interp(
>>>     obs_wavelength,
>>>     transm[“wavelength”],
>>>     transm[“transmission”])
>>> smoothed_transm = Gaussian_filter(
>>>     input=interp_transm, sigma=2)
```
The corrected spectrum is then given as the observed flux divided by the smoothed transmission function on a wavelength by wavelength basis:

```python
>>> corrected_spec = np.divide(obs_flux, smoothed_transm)
```

### 6.2. Correcting Photometry

The `pwv_kpno` package can also be used to correct photometric observations of objects with a known spectral type. To do so, it is necessary to evaluate Equation (6). Note that the product in the numerator, \( S(\lambda) \cdot T(\lambda) \), represents the SED under the influence of atmospheric effects, while \( S(\lambda) \) in the denominator represents the intrinsic SED. For a blackbody observed in the \( i \) band, these values can be found as

```python
>>> # S(\lambda) \cdot T(\lambda)
>>> sed_with_atm = bb_atm.sed(
...   sed_temp, i_band, pwv)

>>> # S(\lambda)
>>> intrinsic_sed = bb_atm.sed(
...   sed_temp, i_band, 0)
```

In practice, the SED of a photometrically observed object may not be available. In such a case it is sufficient to use spectral templates instead. For example, the SED of a star can be reasonably well-parametrized by its observed color.

Using the above results, we evaluate Equation (6) by performing trapezoidal integration with the Numpy package:

```python
>>> numerator = np.trapz(
...   sed_with_atm, i_band)

>>> denominator = np.trapz(
...   intrinsic_sed, i_band)

>>> photo_corr = np.divide(numerator, denominator)
```

The corrected photometric flux of the blackbody is then found by dividing the observed flux by the correction factor `photo_corr`.

### 7. Conclusion and Future Work

Atmospheric transmission in the near-infrared is highly dependent on the column density of precipitable water vapor. By measuring the delay in GPS signals through the atmosphere, initiatives such as the SuomiNet project provide accurate water vapor measurements for multiple, international locations. Through the use of atmospheric models, these measurements provide a means for determining the atmospheric transmission due to precipitable water vapor at each location.

Current methods for removing atmospheric effects commonly rely on fitting for a set of extinction coefficients. Unfortunately, this method does not capture the complex nature of the atmospheric transmission function. When calibrating a photometric image, this introduces errors due to spectral variations of the stars used to determine the extinction coefficients. Atmospheric modeling has the potential to provide an alternative that is not influenced by spectral differences.

The Python package `pwv_kpno` provides models for the atmospheric transmission due to \( \text{H}_2\text{O} \) at user-specified sites. For a given date, time, and airmass, the package uses measurements from the SuomiNet project to determine the corresponding PWV column density along the line of sight. By using a set of MODTRAN models, the resulting concentration is then used to determine the PWV transmission function between 3000 and 12,000 Å.

Future work is planned by the primary author to further explore the relationship between PWV measured by geographically separated GPS receivers. Measurements from two, geographically close receivers can be related by a linearly fitting the PWV concentration measured at both sites. However, this linear relationship does not capture the intrinsic scatter of the measured data. Additional models will be explored that take into account simultaneous temperature, pressure, and relative humidity measurements to improve the ability to model the PWV relationship between GPS receivers.

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**Software:** Python\(^8\), AstroPy (Astropy Collaboration et al. 2013)\(^9\), NumPy\(^10\), SciPy\(^11\), Requests\(^12\), Pytz.\(^13\)

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\(^8\) [http://python.org](http://python.org)

\(^9\) [http://www.astropy.org](http://www.astropy.org)

\(^10\) [http://www.numpy.org](http://www.numpy.org)

\(^11\) [http://www.scipy.org](http://www.scipy.org)

\(^12\) [http://python-requests.org](http://python-requests.org)

\(^13\) [https://pypi.org/project/pytz/](https://pypi.org/project/pytz/)
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