How accurately can we measure the water vapour content with astronomical spectra?

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Introduction

Ground-based spectroscopic observations of astronomical targets inevitably have the signature of atmospheric absorption features imprinted. During data reduction these so-called telluric features are usually removed in order to recover the original spectrum of the astronomical source. However, this telluric "contamination" contains information on the composition and physical state of the atmosphere along the line of sight and during the course of the astronomical observation. Water vapour [1,9], the most common greenhouse gas, is routinely monitored on Paranal (Chile), the observing site of the Very Large Telescope (VLT) of the European Southern Observatory (ESO) in order to identify periods of low precipitable water vapour (PWV), which provide nights of good transparency in the IR[a].

Technique

We have developed the algorithm **molecfit**[b] [2,3], which fits theoretically calculated spectra to telluric absorption features by means of the radiative transfer code LNFL/LBLRTM [6], the line database HITRAN [5], and an atmospheric input profile containing the chemical composition of our atmosphere[c,d,e]. This profile is scaled iteratively to achieve a best fit incorporating a Levenberg-Marquardt χ^2 minimisation algorithm (CMPFIT[f] package). Originally designed for removal of telluric absorption features from astronomical spectra, the precipitable water vapour (PWV) can be determined from the final best-fit profile as side product.

We have used 541 spectra taken with the X-Shooter spectrograph mounted at the VLT. This spectrograph covers the wavelength range from 0.3 to 2.5 μm at medium resolution (R~3300 to 18000) in a single observation. This wavelength range includes many absorption lines from several molecules present in the Earth's atmosphere, e.g. H_2O, CO_2, and CH_4. We have determined the PWV value for each of these 541 spectra observed in 2012 by using specific wavelength ranges affected by water absorption. In order to evaluate the accuracy of the fit, we compare the PWV values derived by **molecfit** with direct measurements obtained with the RPG profiling microwave radiometer LHATPRO[g], which was installed on Cerro Paranal in 2011 [7,9]. This radiometer provides PWV values every few seconds leading to measurements very close in time to any observation taken with X-Shooter. We assume these data as a reference, because the radiometer makes direct measurements of the H_2O line at 183GHz and yields an internal precision of 30μm and an accuracy of about 0.1mm for the PWV (total column).

Results

Figure 1 shows the direct comparison between the **molecfit** and LHATPRO measured PWV values. The **molecfit** derived values are in good agreement with the radiometer data (scatter σ = 0.35mm), but show a minor overestimate of ~0.12mm (see panel (a)). Panel (b) of Figure 1 reveals a slight tendency towards an overestimate of the PWV values for very humid conditions.

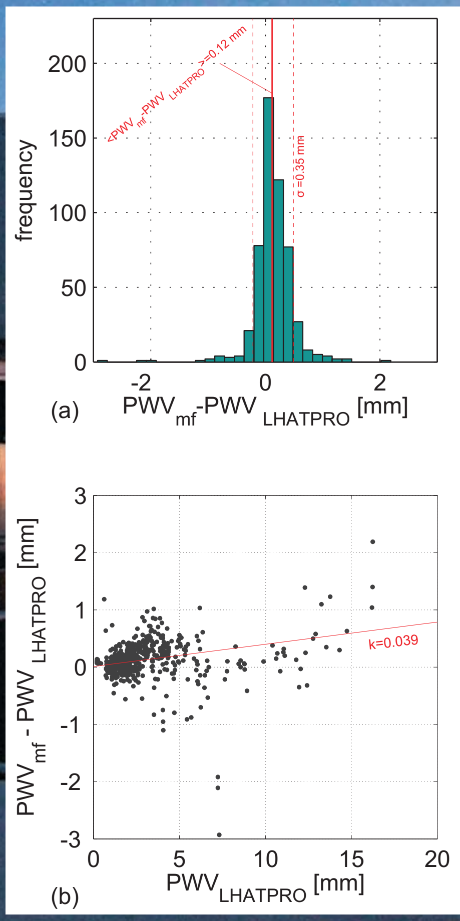

Figure 1: Comparison of the PWV values obtained with **molecfit** with the PWV values measured by the RPG LHAPTRO radiometer. (a) The molecfit based PWV values have a certain scatter (σ=0.35mm), but the mean value provides good coincidence with the measured mean of the reference values. The general slight overestimate (~0.12mm) of the **molecfit** based PWV is probably caused by deviations of the modelled atmospheric input profile from the measured one. (b) The regression line shows a tendency towards larger PWV values derived with **molecfit**.

Discussion and conclusion

The determination of the PWV value is a side product of the **molecfit** software. However, the good agreement and the relatively low scatter of σ=0.35mm indicates that it can be used for determining the PWV values as long as a higher accuracy is not necessary.

There are several sources of error leading to the differences:

(a) the different pointing direction of the telescope (to the astronomical object at arbitrary sky coordinates) and the radiometer (usually to the zenith) thus probing different portions of the atmosphere,
(b) the different field-of-view of the telescope (few arcsec) and the radiometer (3 deg)
(c) the large number of fitting parameters (e.g. instrumental parameters from the spectrograph)
(d) the atmospheric input profile, which is based on several sources of meteorological data[c,d,e].

The possible overestimate of the PWV values at very humid conditions might be related to the low number of data points, as Cerro Paranal is located in the Atacama desert, one of the driest regions world wide.

We have already applied this technique successfully to CO_2 [8]. We conclude that astronomical spectra can be used to monitor greenhouse gases at astronomical observing sites with reasonable accuracy.

Links:
[a] ESO PWV Monitor
http://www.eso.org/observing/dfo/quality/GENERAL/PWV/HEALTH//trend_report_ambient_PWV_closeup_HC.html
[b] **Molecfit** homepages:
http://www.eso.org/sci/software/pipelines/skytools/
http://www.uibk.ac.at/eso/software/index.html.en
[c] Atmospheric Standard Profile
http://www.atm.ox.ac.uk/RFM/atm/
[d] Global Data Assimilation System
http://ready.arl.noaa.gov/gdas1.php
[e] ESO MeteoMonitor
http://archive.eso.org/asm/ambient-server?site=paranal
[f] CMPFIT:
http://www.physics.wisc.edu/~craigm/idl/cmpfit.html
[g] Radiometer Physics GmbH (RPG)
Low Humidity And Temperature PROfiling (LHATPRO) microwave radiometer
http://www.radiometer-physics.de/

References:

[1] Smette et al., 2009, IAU XXVII General Assembly, ESO Chile
[2] Smette et al., 2014, A&A subm.
[3] Kausch et al., 2014, A&A subm.
[4] Molecfit User Manual VLT-MAN-ESO-19550-5772 + references therein
[5] Rothman et al. 2009, JQSRT 110, 533
[6] Clough et al. 2005, JQSRT 91, 233
[7] Kerber et al, 2012, SPIE, 8446, 84463N
[8] EGU2013-7425
[9] Querel et al., 2011, PASP, 123, 222

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