

Using radiative transfer models to study the water vapor content and eliminate telluric lines from high-resolution optical spectra

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I. A simple idea

- Use modern radiative transfer models of the Earth's atmosphere for astronomical applications.
- Two uses:
 - ★ Site testing for water vapor content.
 - ★ Elimination of telluric lines from optical spectra without the need for contemporary telluric standards.

2. The software

The Radiative Transfer Model (RTM) and the retrieval algorithm, incorporated in the SCIATRAN 2.2 software package developed at the Institute of Remote Sensing/Institute of Environmental Physics of Bremen University (Germany), allows to simulate, among other things, radiance/irradiance spectra in the 2400 - 24 000 Å range. In this work we present the applications of RTM to two case studies. In the first case the RTM was used to simulate direct solar irradiance spectra, with different water vapor amounts, for the study of the water vapor content in the Sierra Nevada Observatory (OSN) atmosphere. Simulated spectra were compared with those measured with a spectrometer operating in the 8000 - 10 000 Å range.

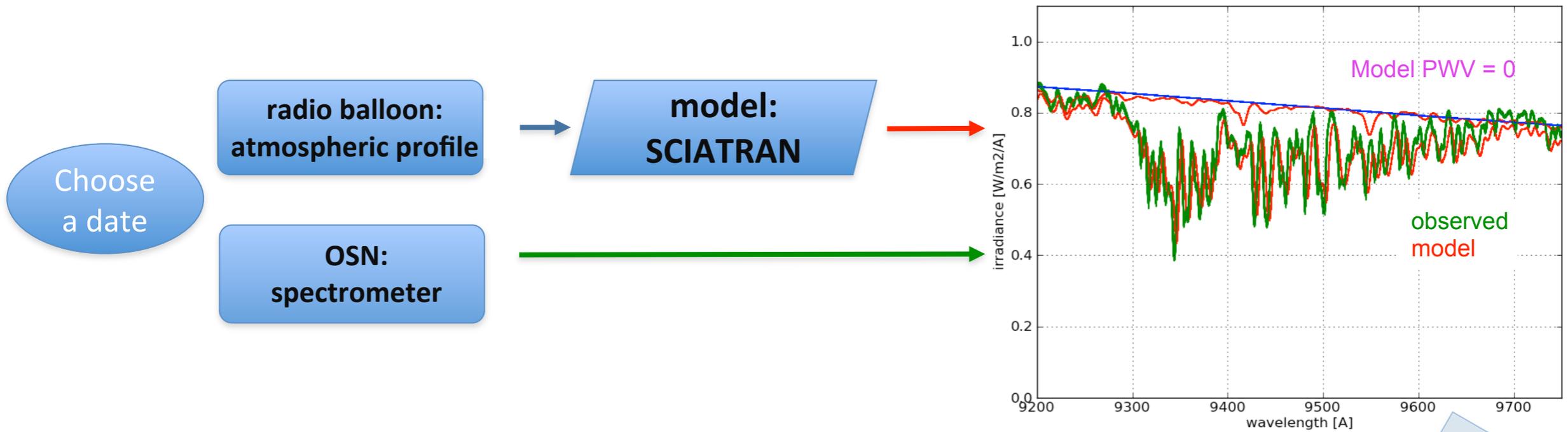
In the second case the RTM was used to generate a telluric model to subtract the atmospheric contribution and correct high-resolution stellar spectra from atmospheric water vapor and molecular oxygen lines. The results of both cases are discussed here.

3. A study of the water vapor content at the Sierra Nevada Observatory

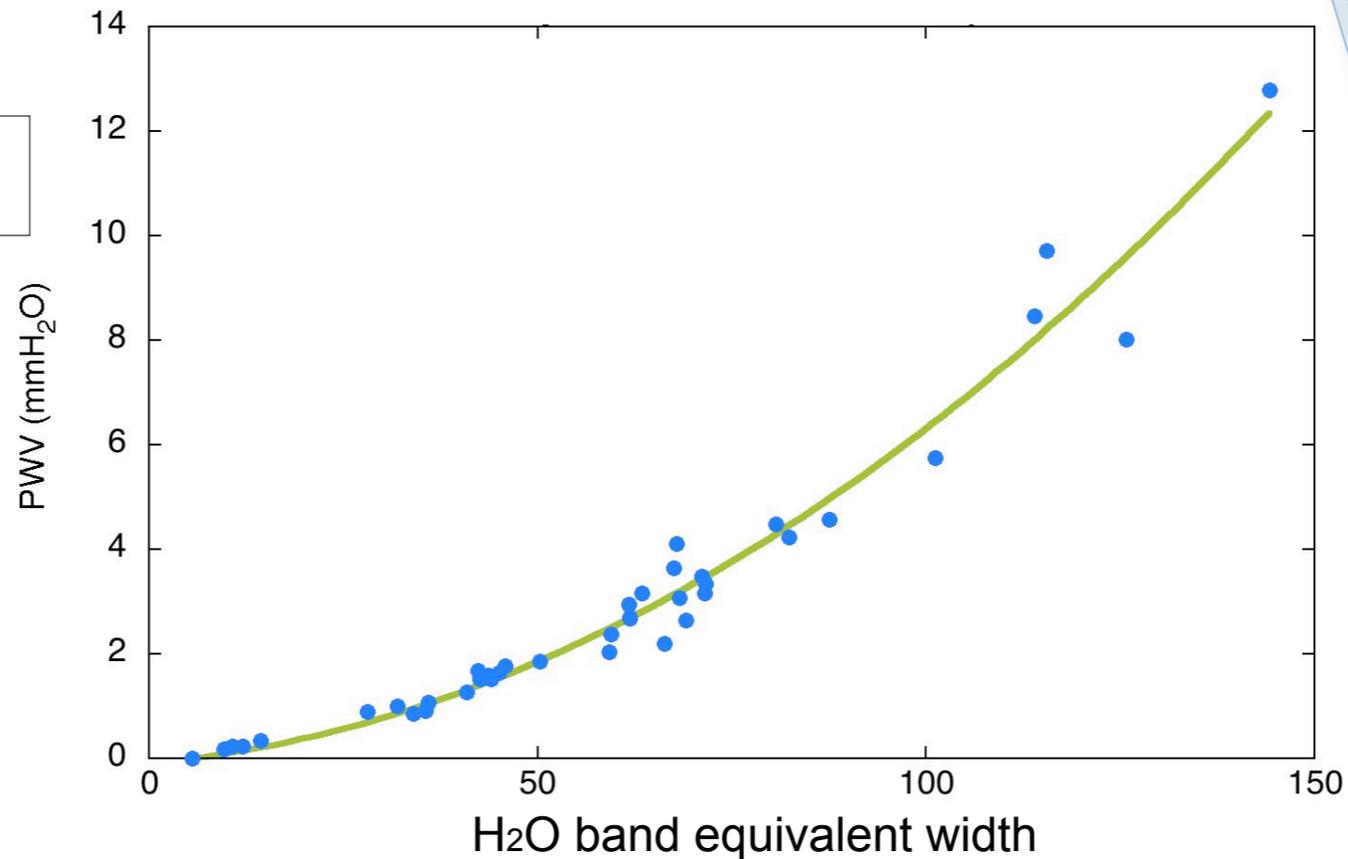
The OSN is the southernmost high altitude (2900 m a.s.l.) location in continental Europe. It is located in Sierra Nevada, Granada, Spain (37.06 N, 3.38 W), less than one km away from the IRAM 30 m telescope. Given the dry climatic conditions it can be considered a very competitive location for MIR-submm astronomical observations.

We obtained direct solar irradiance spectra with an array spectrometer in the 8000 - 10 000 Å range (2.5 Å spectral resolution), during the 2007 - 2009 campaign, for a total of 248 days. The Wyoming University bi-daily radiosounding data were used to provide profiles of Temperature (T), Pressure (P) and H₂O volumetric mixing ratio (vmr) as a function of the geopotential height. The 2003 - 2006 statistics of the radio balloon measurements from Granada (proxy Gibraltar), Canarias (proxy Güimar), and Hawaii (proxy Hilo) shows that OSN is a very competitive site (Figs. 1 and 2). The RTM was used to simulate the direct solar irradiance spectra at OSN and to compare them with those measured with the spectrometer. The equivalent width (EW) of measured spectra in the same water vapor absorption band were also computed.

Figure 1. The extremely dry atmosphere above Sierra Nevada: **an excellent calibration**



Sierra Nevada H₂O band equivalent width vs. PWV
Calibration 2007-2008 SCIATRAN models vs. Observed spectra



OSN PWV_{minimum} = **0.17** mm H₂O
Dome C 25th percentile = 0.18

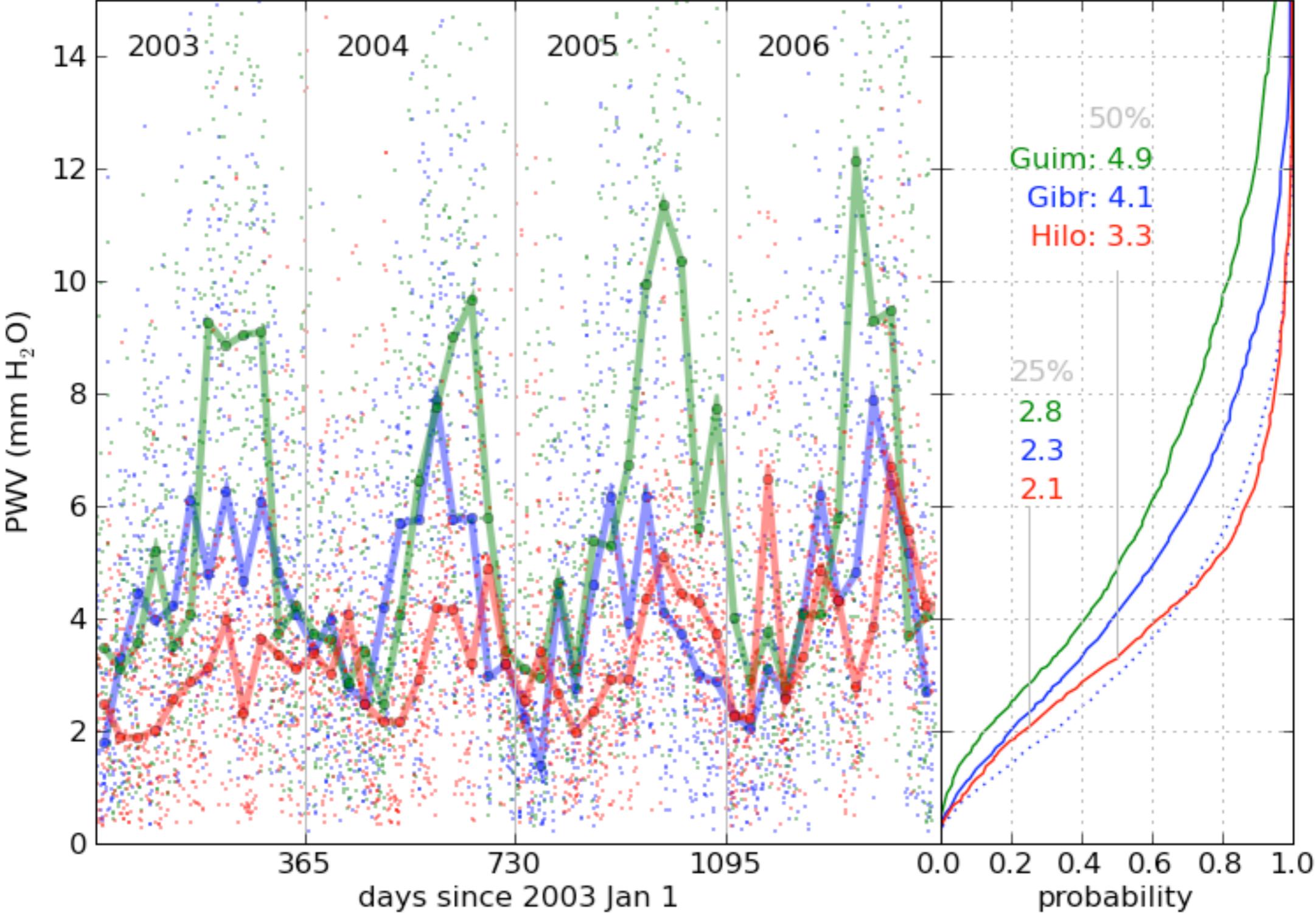
25th percentile:
OSN (2900 m) = **2.3** mm H₂O
Hawaii (4160 m) = **2.1** mm H₂O

3. A study of the water vapor content at the Sierra Nevada Observatory

We used only the spectra observed ± 1 hour from the Gibraltar noon radiosounding (12:00 Z). For each day, the profiles of P , T and H_2O vmr provided by the radiosounding were used to define the model atmosphere in the RTM. For each simulated spectrum the EW in the 9270 - 9700 Å water vapor absorption band was computed, and the corresponding PWV above OSN was associated to it.

This provides the calibration shown in Fig. 1 (bottom), where blue dots are the individual models for 2007-2009 campaign, and the green line is a 2nd order polynomial fit that goes through the 'origin' EW. The 'origin' EW is measured for an atmosphere of zero H_2O column and contributed by the other residual gases (see the low EW pink line in the spectrum above). Notice that we have measured very dry epochs with $\text{PWV} < 0.2$ mm H_2O . We are carrying out an observing campaign to quantify in more detail the statistics of very dry epochs, $\text{PWV} < 1$ mm H_2O , that are certainly not uncommon in Sierra Nevada.

Figure 2. 2003 - 2006 data (left) and statistics (right) of the radio balloon measurements from Canarias (proxy Güimar, green), Granada (proxy Gibraltar, blue), and Hawaii (proxy Hilo, red). In the left panel dots are individual measurements and lines are averages.



4. Elimination of telluric lines from high-resolution optical spectra

- We generate two reference models for 3050 - 10 000 Å.
 - ★ Obtained for the Sierra Nevada Observatory ($h = 2900$ m, $P_{\text{O}_2} = 151$ mbar) but applicable anywhere after rescaling.
 - ★ Only contribution from lines in the output at very high ($R > 100\,000$) spectral resolution.
 - ★ One model without H₂O ("oxygen model").
 - ★ One model with 2.78 mm of H₂O ("oxygen + water model").
- IDL code to fit the telluric spectrum without contemporary telluric standards (Figs. 3-6).
 - ★ Two (O₂ + H₂O) times three (column, velocity, spectral resolution) free parameters.
 - ★ Possibility of defining different wavelength ranges to account for resolution differences in the spectrum.
 - ★ Tested with $R = 30\,000 - 85\,000$ spectra from Hermes (Mercator, La Palma), FIES (NOT, La Palma), FEROS (2.2 m, La Silla), and HRS (HET, McDonald).

Figure 3. Elimination of H₂O telluric lines in the region of the Na D1 + D2 interstellar doublet. Data obtained with HRS/HET at $R = 30\,000$. The red vertical bars mark the location of the strongest telluric lines in this wavelength range. Note the humid conditions under which the spectrum was obtained.

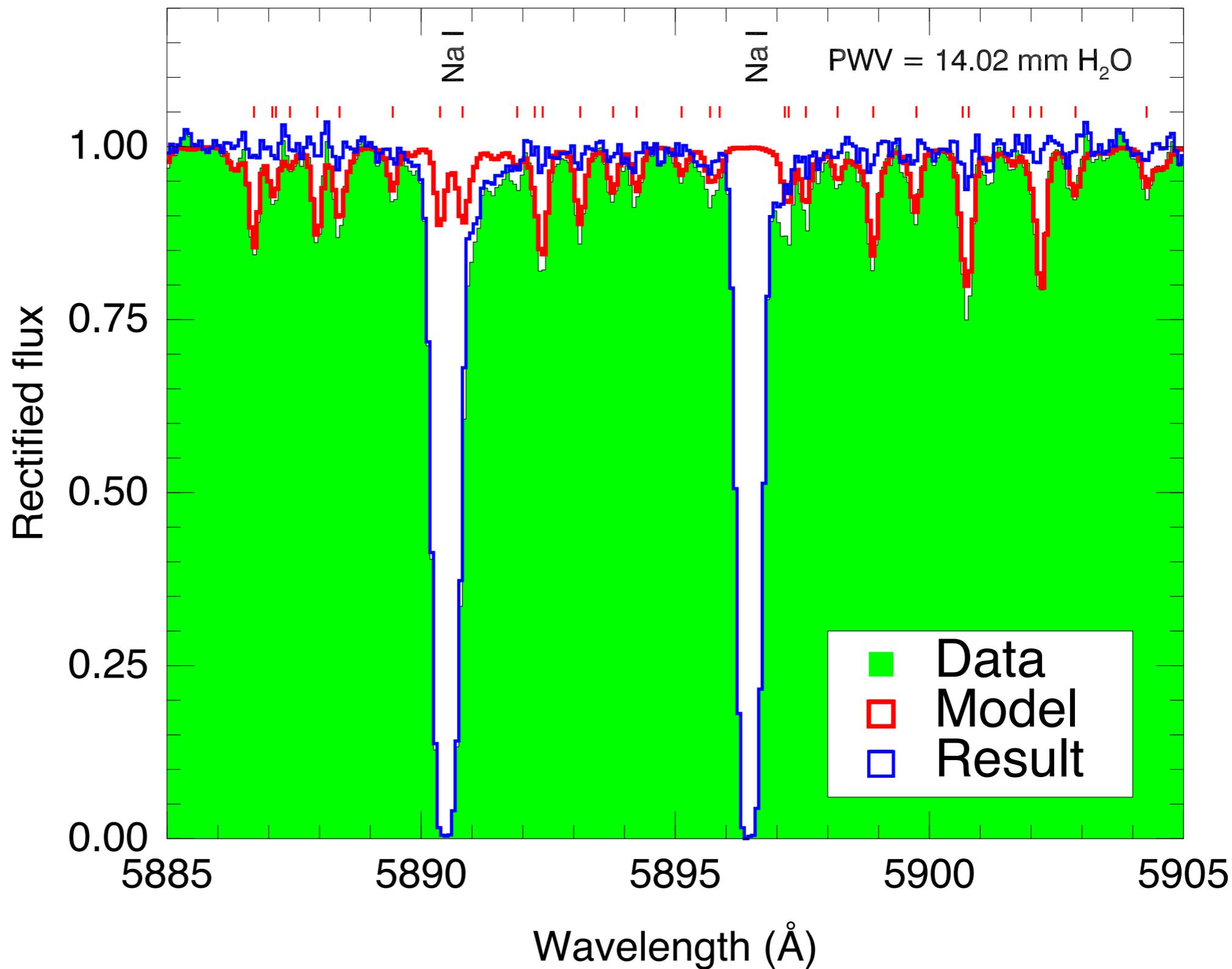


Figure 4. Elimination of H₂O telluric lines in the region of the He II 8237 Å stellar absorption line. This He II line is the best identifier for O stars in the 5500 - 10 000 Å range and is located in the middle of a strong H₂O telluric band. Data obtained with FEROS at $R = 48\,000$. The red vertical bars mark the location of the strongest telluric lines in this wavelength range.

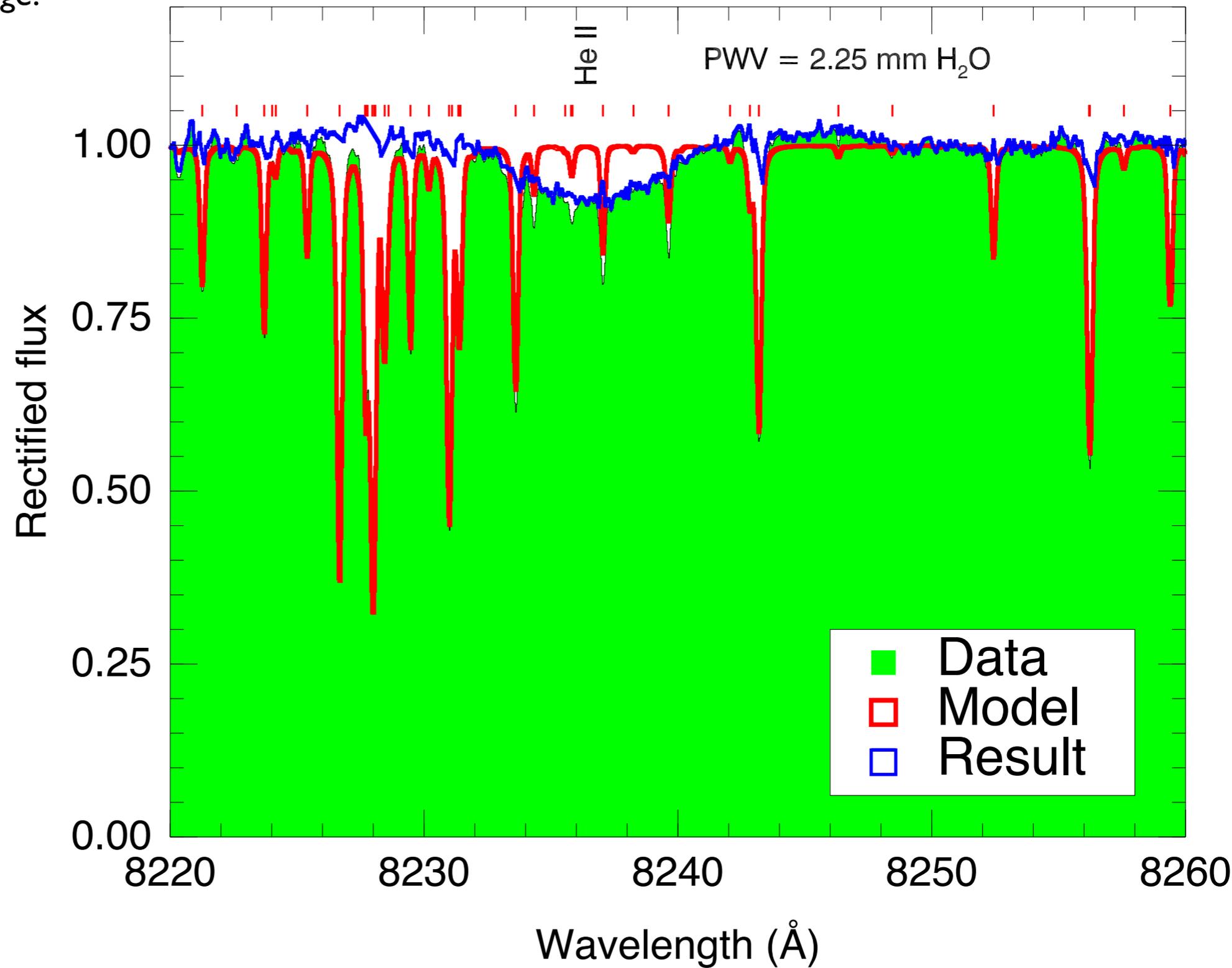


Figure 5. Elimination of H₂O telluric lines in the H α region. Data obtained with HRS/HET at $R = 30\,000$. The red vertical bars mark the location of the strongest telluric lines in this wavelength range.

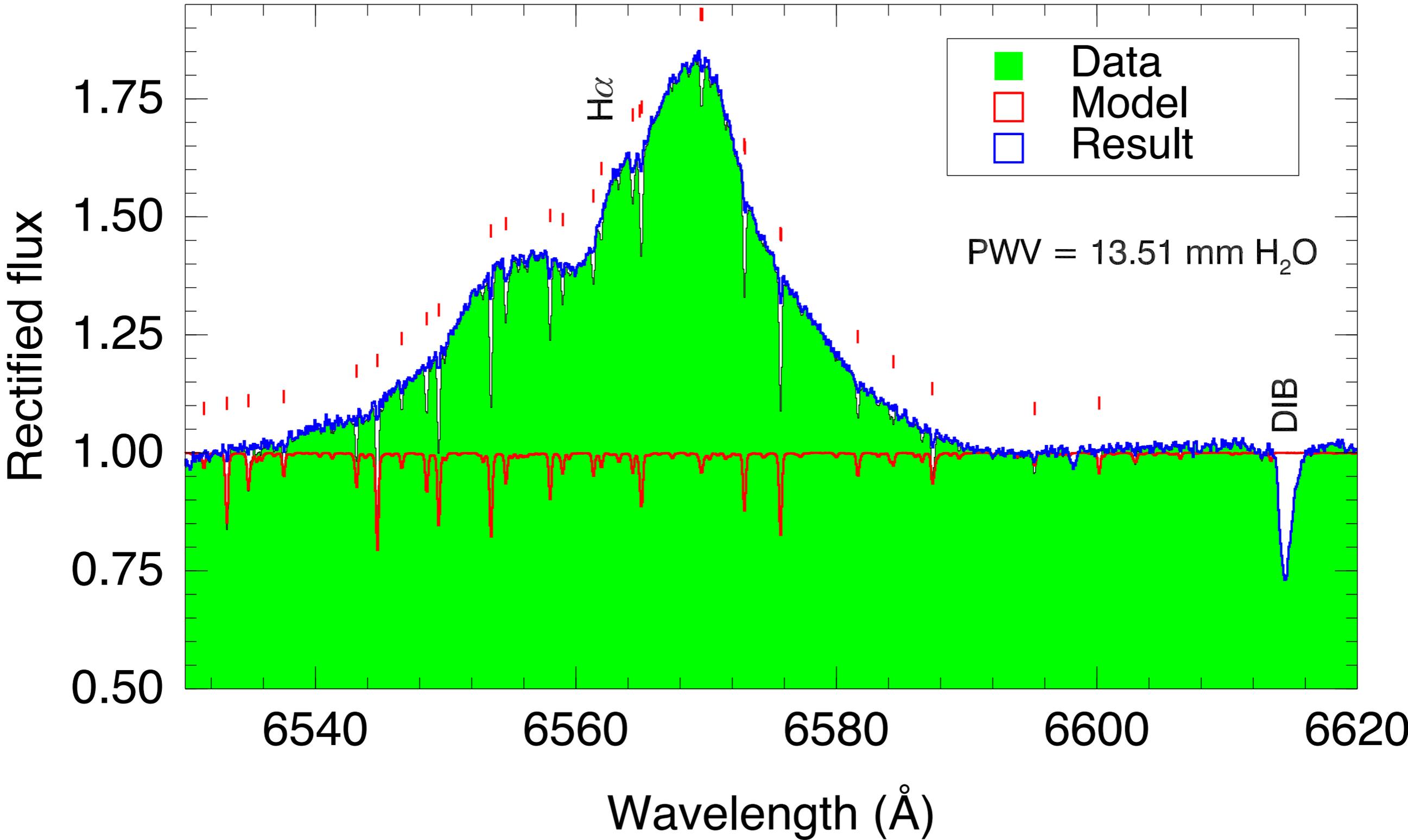


Figure 6. Elimination of H₂O and O₂ telluric lines in the 6300 Å region. Data obtained with FEROS at $R = 48\,000$. The vertical bars mark the location of the weak H₂O (cyan) and strong O₂ (magenta) telluric lines in this wavelength range. The horizontal orange bars indicate the location and approximate widths of the diffuse interstellar bands (DIBs) in this region. Note that the model does not provide an accurate fit for the shortest wavelength (6277 Å) telluric line.

