Publ. Astron. Obs. Belgrade No. 90 (2010), 141 - 146 *Contributed Paper*

A METHOD FOR DETERMINATION OF WATER VAPOR CONTENT FROM SOLAR SPECTRUM: PRELIMINARY RESULTS

M. JOVANOVIĆ[1] and I. VINCE[2]

[1] *Department of Astronomy, Faculty of Mathematics, University of Belgrade, Serbia*
E–mail: miljanajovanovic@gmail.com

[2] *Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia*
E–mail: ivince@aob.rs

Abstract. For precise spectrophotometric observations of solar spectral lines, it is necessary to remove the systematical errors caused by telluric line blending. Calibration methods are usually applied for removing these errors. Calibration in the case of telluric lines that originate from water vapor is more complicated than in the case of molecular oxygen lines, since the amount of water vapor in Earth atmosphere is unpredictable. We present here a method for determination of water vapor amount in atmosphere, based on the measured ratio of water vapor and molecular oxygen spectral line parameters.

1. INTRODUCTION

Absorption by water vapor molecules in the Earth's atmosphere is one of the most important sources of contamination of ground-based spectroscopic observations of the Sun or any other astronomical objects. Therefore, it is of a great interest to reduce the influence of water vapor contamination of measured spectra. For this purpose, one usually introduces two methods: (i) calculating synthetic telluric line profiles or (ii) using a reference (template) spectrum. The second method is unusable in the case of solar spectral observations, since there are no adequate light sources during the daytime. The essence of the first method is the determination of the atmospheric transmission function of water vapor. The ratio of the observed solar spectrum and this function gives the solar spectrum which is corrected for influence of atmospheric water vapor lines.

The atmospheric transmission function depends on the absorption coefficient of water vapor molecule, on the water vapor partial pressure (water vapor concentration), which is related to the relative humidity of the air, and on path of light through Earth atmosphere.

Above an observation site the water vapor concentration is highly variable in the time showing seasonal, daily and random variation. Therefore, for determination of the transmission function, local meteorological data are necessary, which are often nonexistent at the observation site or are not taken at the moment of the observation. This introduces complication into determination of the transmission function and decontamination of solar spectra from water vapor lines. On the other hand, molecular oxygen and some other molecules (i.e. CO_2 , CH_4, N_2O) have constant relative concentration. Having in mind these information, we started to examine the temporal variation of the ratio of water vapor and molecular oxygen line profile parameters (R_p) in an attempt to understand the water vapor spectral line profile variations and the dependence of R_p on the Earth's air humidity. In principle this ratio could be independent on atmospheric parameters (like temperature and pressure) and on the path of the light through Earth atmosphere. A satisfying correlation between the R_p and the relative humidity could enable obtaining the water vapor concentration from solar spectrum without meteorological measurements.

The goal of this paper is to examine the dependence of the ratio, R_p, of water vapor (H_2O) and molecular oxygen (O_2) line profile parameters (equivalent width, EW, and line depth, LD) on relative humidity. The final goal of our investigation is to define calibration curves which give the dependence of R_ps on the amount of water vapor in the air (relative humidity). Using these calibration curves, from observed R_p the relative humidity in the air at the observation time could be obtained.

2. SELECTION OF LINES AND OBSERVATIONS

The choice of spectral lines and spectral range to be observed was governed by the following criteria:

a) The spectral lines should be strong enough for precise measurement of the line profile,

b) If possible, the spectral lines should have as blend-free line profiles as possible,

c) A well-defined continuum should be present in the vicinity of lines,

d) Spectral lines should have proper tabulated parameters since then their transmission function can be determined from theoretical considerations,

e) The spectral range should contain the combination of water vapor and oxygen lines.

Based on these criteria we chose a suitable 0.4 nm wide range of solar spectrum in near infrared ($\lambda \approx$690 nm), which contains a mixture of H_2O and O_2 spectral lines: two O_2 lines and three of H_2O lines. The two prominent O_2 spectral lines in this range are formed by absorption from the lower energy level of the transition with rotational quantum number J=23 of P branch of the (1,0) B spectral band (hereafter P23). In the vicinity of these lines there is a well-defined continuum.

Since we intend to use the parameters of oxygen lines as a measure (standard) for water vapor line parameters variation, it is necessary to verify if they are free from blending by solar and telluric lines (especially water vapor lines). For the purpose we have chosen a sequence of 13 spectral lines of molecular oxygen from the P branch of the (1,0) B spectral band, with odd rotational quantum numbers from J=1 to J=25, which included our oxygen lines (J=23) too. If the spectral lines are free from blend their observed equivalent widths have to fits the theoretical relation between equivalent width and rotational quantum numbers of a branch:

$$ln[EW_J/(2J+1)] = a + b \times J(J+1).$$

The observation, reduction and analysis of the dependence are given in more detail in article by Vince et al. (2006). The plot of $ln(EW_J/2J+1)$ values against J(J+1) is presented in Fig. 1. As one can see, the equivalent width of the P23 spectral line is perfectly fit the regression line. Consequently, this line fulfills our b) criterion. In contrary, the P21 spectral line, for example, is confessedly disturbed with other spectral line(s) of solar or telluric origin and it would not be enough good for our purpose.

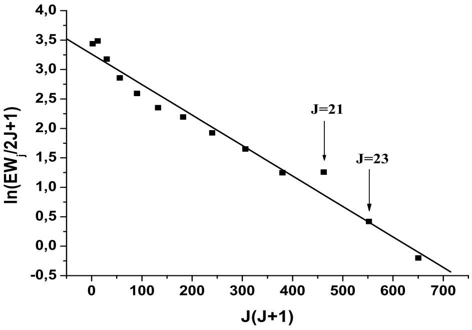

Figure 1: **ln(EWj/2j+1)** versus **J(J+1)**. Dots represent the observed values and the line is the best linear fit(adopted from Vince et al. (2006).

Observations of the P23 were made at Astronomical Observatory of Belgrade on 4, 9, 13 July and on 3 and 15 August, 2007. The solar telescope was equipped with Litrow type spectrograph with effective focal length of 9 m (Kubičela 1975). At that time the detector was a SBIG ST6 CCD camera, which chip covers about 0.4 nm range of spectrum in third spectral order. In the left picture of the Fig. 2 the CCD image of the spectrum from our chosen spectral range with P23 is presented. The right side panel shows a plot of the relative intensity dependence on the wavelength.

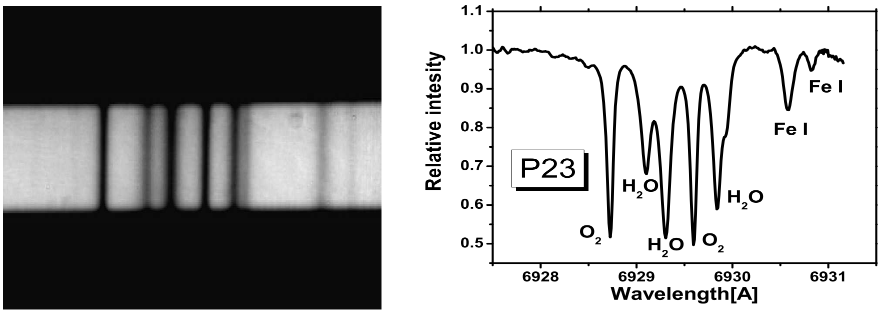

Figure 2: The CCD image and plot (from SPE package) of the solar spectrum with the doublet of P23.

3. REDUCTION AND ANALYSIS

The CCD images have been reduced using *MaxIm_DL* software. The dark-frame corrections were performed automatically by CCD camera software in the first several observations, and later the dark frames were taken separately, usually at the beginning, in the middle and at the end of observation, and then subtracted from the images. For determining the local continuum level we introduced a second degree polynomial function. Each spectrum is normalized to this continuum level. The obtained spectra for five observation days are shown in Fig. 3.

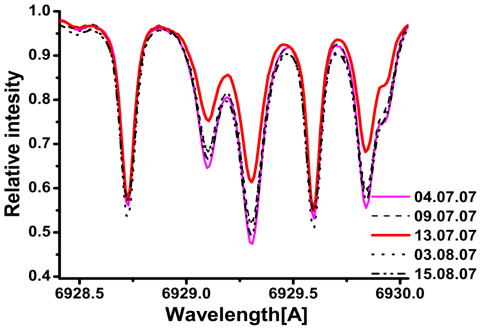

Figure 3: The obtained spectra for five observation days.

By simple visual inspection of the plots, it is evident that the water vapor lines changes, while the oxygen line profiles stay the same for different days of observation. This variability of water vapor line profiles we refer to different quantity of water vapor in the air.

We found Lorentz function (profile) as a valid approximation for observed telluric line profiles (see Table 1). From the observed spectra, the five partially overlapped spectral line profiles were disentangled by applying this function using non-linear least-squares method. Some parameters(χ^2/DoF, DoF = degrees of freedom, coefficient of determination (R^2) and Y offset), which measure the combined Lorentzian fits quality are listed in the Table 1. In the average (R^2) is about 0.98. Therefore, we can conclude that the Lorentzian profile is a very acceptable function for fitting of our observed spectral line profiles. From the corresponding Lorentz profile parameters, the equivalent widths and line depths of these five spectral lines were obtained. Afterwards, the ratio of water vapor and molecular oxygen line profile equivalent widths (R_{EW_i}) and line depths (R_{LD_i}) are calculated using the (O_2) 692.8728 nm and (O_2) 692.9599 nm line profile parameters as divisors; these ratios are indexed width i=1 and i=2, respectively.

The data for relative humidity were obtained from measurement of the Republic Hydrometeorological Service of Serbia, which is located about 3 km south-west from our Observatory. The humidity data for the time of our observation are obtained from linear interpolation of meteorological humidity data.

Table 1: The χ^2/DoF, R^2 and Y-offset for different days of observation.

Date	04.07.07.	09.07.07.	13.07.07.	03.08.07.	15.08.07.
χ^2/DoF	0.00049	0.00031	0.00018	0.00031	0.00035
R^2	0.973	0.981	0.985	0.982	0.981
Y offset	1.0034	1.0037	1.0011	1.0015	1.0047

In order to estimate of the overall accuracy of determination of (R_{EW_i}) and (R_{LD_i}) ratios for five spectral lines we calculated their standard deviations (STD) from daily measured spectra (about 10 spectra per day). Then we average them for five days of observations. These average values for spectral lines (identified by the appropriate wavelengths) are listed in the Table 2. As one can see from the table the largest value for EW is 0.14, which is about an order of magnitude larger then the rest of the obtained values. At the same time, the STD of the LD of this line is not differs significantly from other values. We think that this large value of the STD is due to reconstruction of the line profile with our disentangling method. We need further observations to prove this assumption.

Table 2: The list of the normalized standard deviations to the first and to the second line of the oxygen.

	Normalized to the first line of the oxygen				Normalized to the second line of the oxygen			
λ	6929.1	6929.3	6929.6	6929.9	6928.7	6929.1	6929.3	6929.9
STDEW	0.023	0.14	0.017	0.027	0.022	0.021	0.038	0.039
STDLD	0.013	0.022	0.010	0.021	0.011	0.014	0.024	0.022

Table 3: The list of the parameters and errors of the linear fitting.

Parameters related to the EW normalized to the first oxygen line							
No. line (H_2O)	A	B	Error A	Error B	R	STD	P
I	76	-44	12	12	-0.91	3.1	0.032
II	81	-31	12	8	-0.93	2.9	0.024
III	72	-26	12	9	-0.88	3.6	0.048
Parameters related to the LD normalized to the first oxygen line							
No. line (H_2O)	A	B	Error A	Error B	R	STD	P
I	70	-59	20	31	-0.74	5.0	0.147
II	78	-44	23	23	-0.75	5.0	0.140
III	72	-45	24	27	-0.69	5.5	0.197

Parameters related to the EW normalized to the second oxygen line							
No. line (H_2O)	A	B	Error A	Error B	R	STD	P
I	70	-34	14	13	-0.84	4.1	0.073
II	74	-23	14	8	-0.87	3.8	0.058
III	67	-21	14	9	-0.83	4.3	0.085
Parameters related to the LD normalized to the second oxygen line							
No. line (H_2O)	A	B	Error A	Error B	R	STD	P
I	70	-59	19	30	-0.75	5.1	0.145
II	77	-43	22	22	-0.76	5.0	0.138
III	71	-45	23	27	-0.70	5.5	0.191

We chose linear fit ($Y = A + B * X$) for determination of the correlation between and humidity of the air (calibration curves). In Fig. 4 the correlation between the humidity and R_{EW_1} and R_{LD_1} (divisor is the oxygen line at 6928.7 nm) are shown.

In the Table 3 parameters A and B, errors of these parameters, correlation coefficient (R), standard deviation (STD) and probability (P) that R is zero (for the three water vapor lines in P23 region), are listed. In general, the linear fit of equivalent

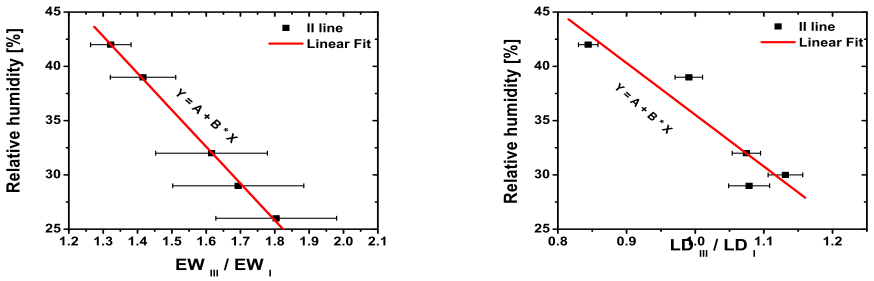

Figure 4: Calibration curves for the second line of the water vapor.

width ratios is better then that of the line depth ratios. The best fit (according to the correlation coefficient value R=-0.93) is achieved for the ratio of equivalent width of the second water vapor line and the first oxygen line. The ratio of the equivalent width of the first water vapor spectral line and the first oxygen spectral line also gives a very good fit (R=-0.91). The rest of fits are worse than these two are.

4. CONCLUSIONS

We have shown that there is a significant difference between the water vapor spectral line profiles and their parameters (EW and LD) for days with different humidity, while the oxygen line profiles do not change in frame of errors of measurements.

The ratio of water vapor and oxygen spectral line parameters is correlated with the relative humidity. Our analysis has shown that a linear function could be an adequate approximation for this relationship and could be used as a calibration function. The best fit has been achieved for the ratio of the equivalent width of the water vapor line at 6929.3 Å and the oxygen line at 6928.7 Å. However, the errors of our fitting parameters are too large. We suppose that these large errors are due to a small number (five) of observations and to large errors of the line profile parameter measurements.

We are planning to continue our observation to increase the number of data. To improve the preciseness of our observations we replaced the old SBIG ST6 CCD camera with a new Apogee Alta U47+ CCD camera, which is more sensitive in the infrared spectral region.

Acknowledgments

This work is a part of the project ”Stellar and Solar Physics” (No. 146003) supported by the Ministry of Science and Technological Development of the Republic of Serbia. We appreciate the work on observing the Sun, by Ivana Milić and Neda Stojković from the University of Belgrade, Serbia.

References

Kubičela, A.: 1975, *Publ. Astron. Obs. Beograd*, **20**, 47.

Vince, I., Kos, P., Latković, O., Martinović, N., Gošić, M., Stojadinović, J.: 2006, *Serb. Astron. J.*, **173**, 101.

Wood, E.: 2003, *Telluric Line Removal in Astrophysical Spectroscopy*, ASEN/ATOC 5235.