INTERCOMPARISON OF SOLAR RADIOMETER AND RADIO SOUNDING WATER VAPOR COLUMNS FOR ATMOSPHERIC PROCESSING OF IMAGING SPECTROSCOPY DATA

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ABSTRACT

Two methods for the measurement of the column water vapor in the atmosphere are compared with respect to their usefulness for imaging spectrometer campaigns. First, in situ measurements of 26 radiosonde launches are integrated with height to obtain the water vapor column. Second, simultaneous ground irradiance measurements using a sun photometer are inverted to column water vapor amounts. An exact calibration of the solar radiometer is performed to increase the measurement accuracy. The results obtained by the radiometric method differ from the in situ measurements within the relative accuracy of the balloon-borne humidity sensors. The largest differences are attributed to dusty, highly humid atmospheric conditions. We conclude that sun photometry is a viable substitute to in situ water vapor measurement for the validation of atmospheric correction methods and in flight sensor calibration.

KEY WORDS: *SPECTRAL SOLAR RADIOMETER, RADIO SOUNDING, ATMOSPHERIC WATER VAPOR*

1 INTRODUCTION

Scientific investigations on imaging spectrometer data requires external information on the optical properties of the atmosphere. These properties strongly depend on the amount of aerosols and atmospheric water vapor. In situ measurements of the vertical profile of temperature, relative humidy and concentration of selected trace gases (e.g. ozone) may be performed using balloon-born radiosondes (Figure 1). However, this data is not always available during imaging spectrometer experiments. For atmospheric correction and inter-calibration purposes it is often sufficient to know the mass column of the absorbers and scatterers. The corresponding optical depths can be determined by measuring the extinction of the solar radiation at relevant wavelengths. The main goal of this paper is to check the reliability of such radiometric procedures compared to in situ measurements.

The tracking Reagan solar radiometer ("Sun Photometer"; see Figure 2) measures the direct irradiance of the sun in 10 spectral bands located at specified central wavelengths (382, 410, 501, 611, 669, 721, 780, 872, 940, and 1033 nm). The bandwidth is about 10 nm. The first part of this paper deals with the calibration of the solar radiometer at Mount Lemmon, Arizona, USA (2791 m a.s.l.), and at the Swiss high alpine research stations at Jungfraujoch (3580 m a.s.l.) and Weissfluhjoch (2430 m a.s.l.). In the second one we compare the water vapor columns derived from the 940 nm channel with the integrated water vapor densities taken

Figure 1 Radiosonde for air pressure, temperature, humidity, wind, and ozone sounding.

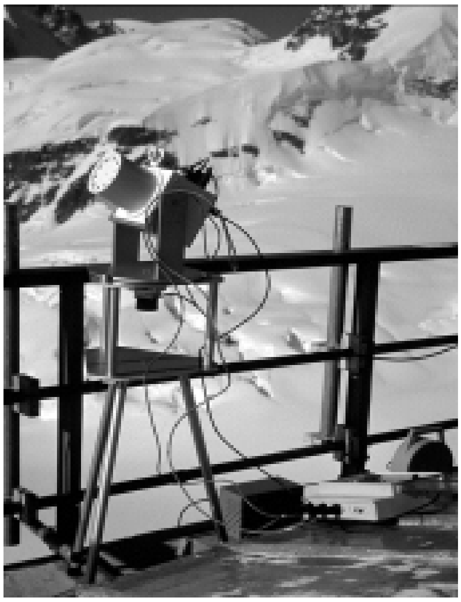


Figure 2 Reagan solar radiometer with 10 spectral bands between 382 and 1033nm during a high altitude calibration campaign.

from radio soundings. The field experiments were performed in the Valle Mesolcina (Southern Switzerland) and in the Po Valley (Italy).

2 CALIBRATION OF THE SOLAR RADIOMETER

The calibration of the relative counts of the solar radiometer was performed using the Langley plot method [see e.g. Schmid, 1995 or Forgan, 1994]. The direct solar irradiance during a sun rise period at stable atmospheric conditions can be written as

$$E(\lambda) = E_0(\lambda)e^{-\tau_0^* m(\theta)}, \tag{1}$$

where $E(\lambda)$ is the solar irradiance measured by the radiometer, $E_0(\lambda)$ is the extraterrestrial irradiance, τ_0^* is the vertical optical thickness of the atmosphere and $m(\theta)$ is the relative airmass at the solar zenith angle θ. In the approximation (1) the radiation scattered into the field of view of the instrument is neglected compared to the direct radiation. The relative air mass is often approximated by $m(\theta) = 1/\cos\theta$. A more sophisticated expression for $m(\theta)$ is given by Kasten and Young (1989) who take into account the refraction of the radiation path in the atmosphere.

The output signal $V(\lambda)$ is assumed to be proportional to the solar irradiance $E(\lambda)$. Inserting this correlation in Eq.(1) and taking the logarithm yields the linear function (the wavelength dependency is omitted in the notation)

$$\ln(V) = \ln(V_0) - \tau_0^* m(\theta). \tag{2}$$

As V and m are known for a zenith angle range given by the measurement time period, the data can be extrapolated to the expected extraterrestrial signal V_0 at $m = 0$. This method is known as the Langley plot calibration. The slope of the straight line is the vertical optical thickness τ_0^*. The calibration constant V_0 is strictly valid for the calibration day. For any other date V_0 has to be corrected according to the actual sun-earth distance.

The linear correlation (2) is accurate only for those channels which are not located in absorption bands, in particular outside the 721 and the 940 nm water vapor bands. Within these bands the Langley plot approach has to be modified according to results obtained with radiative transfer codes such as MODTRAN [Kneisys et al., 1995] (for details see Schläpfer, 1998). The angular optical thickness $\tau_0^* m(\theta)$ is split into the aerosol thickness $\tau_{ae,0}^* m(\theta)$ and the water vapor thickness $\tau_{wv}^*(\theta)$, the latter being approximated by the power law

$$\tau_{wv}^* = k(mPW)^b, \quad \text{with} \quad \tau = e^{-(\tau_{ae,0}^* m(\theta) + \tau_{wv}^*(\theta))}. \tag{3}$$

The actually observed parameter is the total transmittance τ as a function of the optical thickness τ^*. PW is the amount of precipitable water in cm, k and b are parameters obtained by fitting the right term in Eq.(3) to MODTRAN simulations of the transmittance at the sun photometer level.

Figure 3 shows the calibration constants determined by RSL at Jungfraujoch and Weissfluhjoch (1996 and 1998) together with those measured at Mount Lemmon (AZ, USA, 1995), provided by the instrument manufacturer. The humidity at Mount Lemmon and at Weissfluhjoch was very low, whereas the measurements at Jungfraujoch were perturbed by advected clouds and moisture. The results suggest that there is a degradation of the sensors sensitive at lower wavelengths. This effect may be also caused by processing incaccuracies. However, the remaining channels have quite a good stability. The use of the modified Langley plot increases the calibration constant V_0 in the 940 nm channel by 5 to 15% and decreases the relative RMS by about 1%. The RMS deviation of all calibration measurements are depicted in Figure 4.

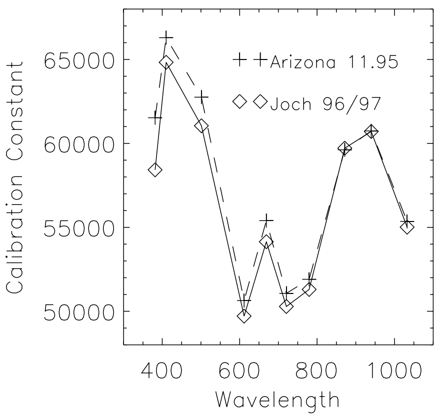


Figure 3 Calibration constants determined at Mount Lemmon (1995), at Jungfraujoch (1996), and Weissfluhjoch (1998); derived by the modified Langley plot method.

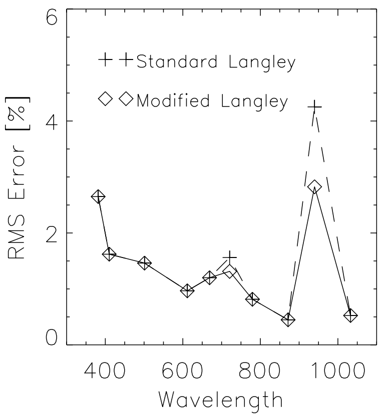


Figure 4 RMS deviation of 6 calibtration runs between fall 1995 and winter 1998 for the standard and the modified Langley plot.

3 WATER VAPOR MEASUREMENT USING THE 940 NM ABSORPTION BAND

The precipitable water *PW* is calculated on the basis of the continuum interpolation, followed by inverting the modified Langley equation (3). First, the total transmittance τ_{940} at 940 nm due to aerosol scattering and water vapor absorption is calculated directly from the calibrated data. Then, the absorbtance due to aerosols is obtained by interpolating the values from the adjacent channels to 940 nm. Inverting Eq.(3) by introducing the corresponding transmittance values yields

$$PW = \left[\frac{\ln \tau_{940} - \ln \tau_{940,ae}}{-k\, m^b} \right]^{1/b} . \tag{4}$$

The constants b and k are crucial for the inversion function (4). They therefore have to be derived carefully from the transmittance values simulated with MODTRAN. The values for average midlatitude summer conditions are k=-0.58 cm^{-1} and b=0.63, respectively.

4 WATER VAPOR PROFILES ON THE BASIS OF RADIO SOUNDINGS

A mobile radio sounding equipment was used to measure the vertical profile of the atmosphere. The sondes are capable of measuring air pressure, temperature, relative humidity, wind velocity and direction, as well as the partial pressure of ozone up to about 15 km a.s.l.. For our purpose the top altitude was set to 6 km. Figure 5 shows the results of a typical ascent. The relative humidity was converted to water vapor density and integrated up to 6 km a.s.l. Above that level, the amount of water turned out to be negligible.

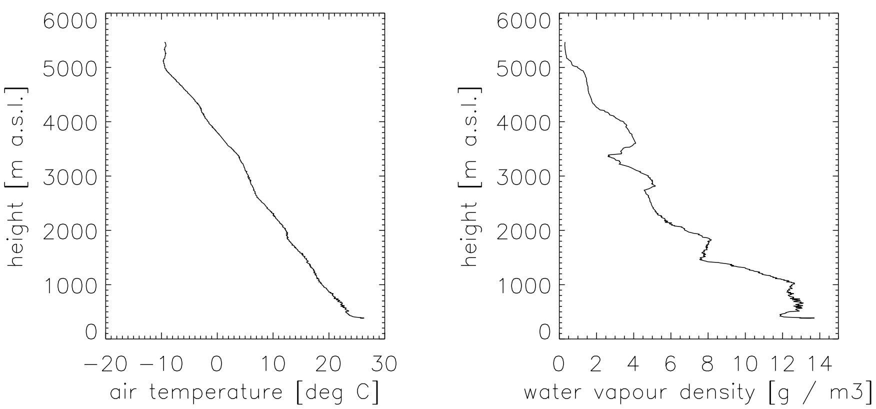
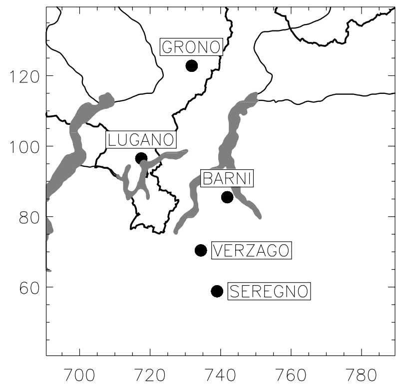


Figure 5 Typical temperature and water vapor density profile on a clear summer morning.

5 THE FIELD EXPERIMENTS

In two field experiments of the air quality project VOTALP (Vertical Ozone Transport in the Alps [Furger et al., 1996]) radio soundings were performed at 1 to 2 hours intervals from dawn to dusk. The dense availability of sounding data offers the opportunity to compare atmospheric water vapor profiles with radiometer based precipitable water for a whole daytime cycle. On 6 days the solar radiometer was operating simultaneously with the soundings.

The experiments in summer 1996 were made on 3 days at Grono which is located in the Valle Mesolcina in Southern Switzerland. This valley is surrounded by mountains of about 3000 m a.s.l. altitude. It leads to the Ticino region and is connected to the Po Valley. The measurements in summer 1998 took place in the Po Valley, north of Milan. On the first day of the intercomparison, two soundings were made at Seregno in a completely flat area and two at Barni in the hilly region of Lake Lecco. During the second and the third day, the measurements were performed at Verzago which is located on a small elevation inbetween. Further details about the sites are given in Figure 6.



site	altitude [m a.s.l.]	date
Grono(CH)	320	August,16-18, 96
Barni (I)	635	June 4, 98
Verzago (I)	388	June 5-6, 98
Seregno (I)	224	June 4, 98

Figure 6 Location of the experimental sites of the VOTALP field experiments.

4 RESULTS

Twenty-six radiosoundings of the data sets acquired in 1996 and 1998 were compared to the continuous sun photometer readings. The radiometer data was averaged over t ± 5 min., t being the reference time. Because a typical sounding takes 20 to 30 min to reach 6000 m a.s.l, t was set to 15 min after launch. In the top graph of Figure 7 the precipitable water measured by the radiosondes is plotted together with the radiometer data, both taken at Grono. The bottom graph shows the optical thickness τ_0^* of the channels 1 (381nm) and 3 (501nm). The optical thickness is a measure of the total aerosol content, dust, and cloud cover. For clear sky conditions it remains below 1.0. If there are heavy dust, fog or cirrus clouds within the optical path to the sun, the optical thickness may exceed values of 1.5 to 2.0. Moreover, the wavelength dependence of τ_0^* is an indicator of the particle size distribution of the aerosols.

The data of Grono show a significant diurnal variation of the precipitable water PW in the atmosphere. In the early morning before sunrise and shortly afterwards, PW decreases to values between 1.2 and 1.8 cm. This is particularly evident on the second and the third day. Later, the value increases again to 3.0 - 3.5 cm. We suppose that this diurnal variation is due to the transport of dry air from the mountains during nighttime and to the advection of moist air by the valley wind during the day. The analysis of these phenomena and of the aerosol data is beyond the scope of this paper and will be treated separately.

From the data in Figure 7 it is evident that the precipitable water calculated on the basis of the radiometer measurements is a rather smooth function of time. Conversely, the optical thickness shows substantial fluctuations during the day due to high level clouds and dust. We conclude that the continuum interpolation method is stable enough to filter out aerosol disturbances for the water vapor retrieval procedure.

The difference between radio sonde and radiometer data is about 0.05 cm when the air is clean (August 17) and about 0.1 cm under more disturbed conditions. This amount corresponds to a relative difference between 2 and 8%. The agreement is much worse in the early morning than during daytime. This effect can be explained by the fact that the relative humidity is close to saturation. From a set of comparisons between the humidity signals of the sonde before launch and the reference instrument at ground level, we conclude that at high relative humidity the hygrometer readings of the radio sonde are not very reliable, the error being up to 10-15%. Under normal conditions (about 40 to 60%) the error is about 5% relative humidity.

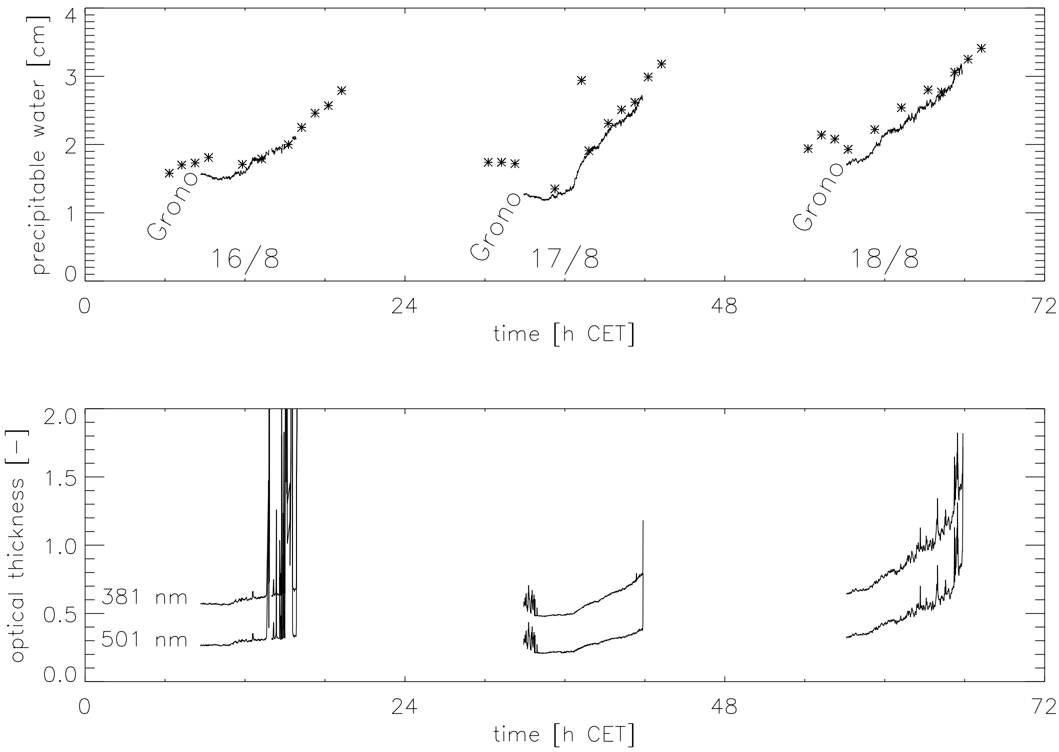


Figure 7 Top: Precipitable water measured by radio sondes (asterisks) and by the solar radiometer (solid line) at Grono. August 16 - 18, 1996. Bottom: Optical thickness of the radiometer channels 1 (381 nm) and 3 (501 nm).

Taking this inaccuracy into account, the agreement between the radiometer and the radio sonde data is very good on the first and the second day. Conversely, tha data match less on the third day due to a deterioration of the weather conditions leading to precipitations at the end of the day.

The agreement in the Po Valley experiment in 1998 was similar (Figure 8). At Seregno two sondes were launched. The atmosphere was substantially disturbed by the Milan dust leading to a worse match of data compared to the Grono results. The Barni comparison is not representative because it is based on only one ascent due to an early sunset behind the mountains. The data of Verzago on June 5 agree well because of the clearness of the day. On the last day, there was an increasing dust cover which is responsible for worse results.

In general, the precipitable water measured by the sun photometer on clear days is about 0.05 cm lower than the value derived from the radiosonde. For higher optical thicknesses this deviation increases to 0.1 cm. Two reasons are supposed to be responsible for these systematic differences: As mentioned above, the readings of the radio sondes tend to overestimate the water vapor at high relative humidity (i.e. greater 80%). This effect can cause errors close to saturation, which may easily occur under heavily dusty conditions or in the cool morning hours. The radiometry, on the other hand, is affected by upcoming low level clouds, since the instrument does not measure the humidity signal of the radiation along the full light path due to absorption and scattering in the clouds. However, this effect is not relevant for high altitude cirrus clouds, since in that case more than 99% of the water vapor is located below the cloud level.

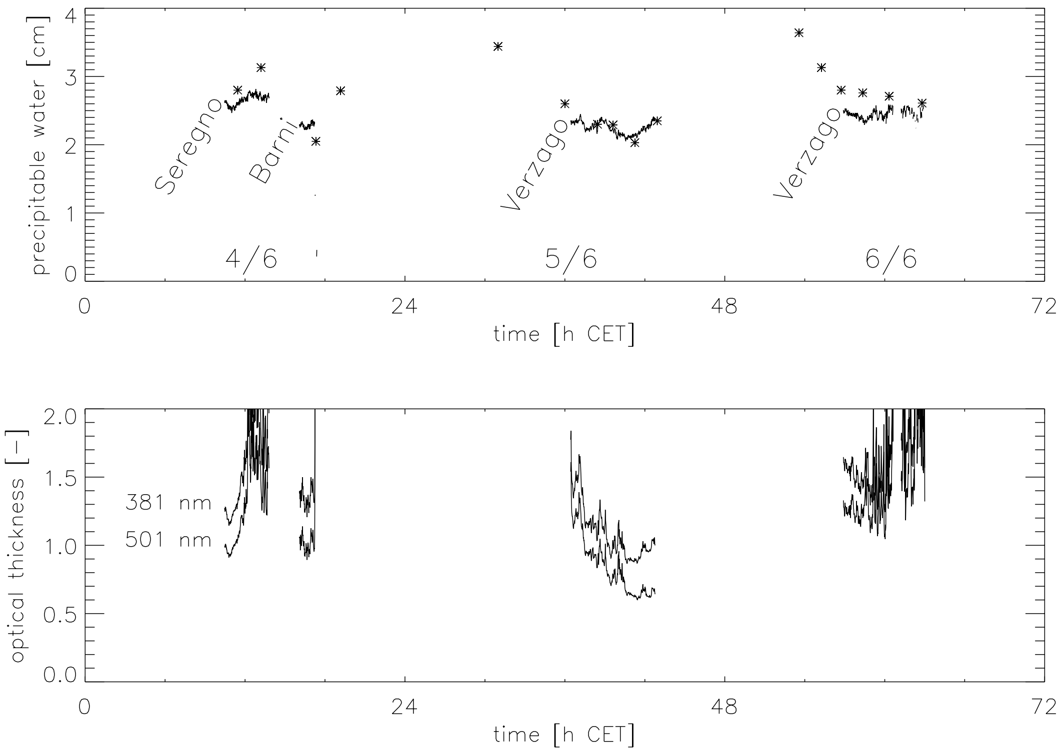


Figure 8 Top: precipitable water measured by radio sondes (asterisks) and by the solar radiometer (solid line) at Seregno, Barni and Verzago. June 4 - 6, 1998. Bottom: optical thickness of the radiometer channels 1 (381 nm) and 3 (501 nm).

5 CONCLUSIONS

The intercomparison between solar radiometer and radio sonde measurements shows a good agreement. The residual differences between radiometric and in-situ measurements yield an estimate of the relative accuracy which is below the 5% limit for clear sky conditions. Precipitable water and aerosol optical thickness can be processed in a reliable manner from radiometric ground measurements as provided by sun photometry. The radiometer signal of water vapor could be clearly discerned from the aerosol signal.

Radiometric ground truth measurements for column water vapor are reliable within the accuracy of true in situ measurements. We conclude that the launch of radiosondes is not absolutely necessary for field measurement campaigns if radiometric ground instruments are available. The balloon soundings, however, are still useful for conditions where vertical temperature and humidity profiles are indispensable. This is particularly the case for the data processing (e.g. the atmospheric correction) of hyperspectral images taken over mountaineous terrain, since the properties of the optical path from the ground to the sensor depends strongly on the terrain elevation of the observed pixel.

The short-term variations of the water vapor and of the optical thickness could be quantified as an important support of imaging spectroscopy data calibration. In two airborne imaging spectroscopy experiments in Central Switzerland in summer 1996 and 1997 the Digital Airborne Imaging Spectrometer (DAIS) was validated against ground truth measurements. Radiometer and radiosounding data were used for atmospheric corrections as well as for the comparison of image-based and radiometer-based water vapor [Schaepman et al., 1997]. The sun photometer measurements turned out to be a very useful data source supporting such intercalibration and validation experiments.

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