Calibration of near-infrared absorption band for a sun-photometer

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Abstract: The atmospheric transmittance properties for three near-infrared channels of POM02 skyradiometer at the wavelengths of 1020 nm, 1627 nm, and 2200 nm, were studied by using a combined atmospheric radiative transfer model (CART). Results showed that, the extinctions at the bands of 1020 nm, 1627 nm, which are located in atmospheric window channel, obeyed the Beer-Lambert law. For the 2200 nm channel located in an absorption band, the absorption exhibited an exponential distribution. Then these channels of POM02 skyradiometer were calibrated with traditional Langley method and modified Langley method, respectively. Two calibration methods were applied for four clear days. It proved that the accuracy of derived transmittance has been improved by 3.8% using modified Langley method to 2200 nm channel.

Key words: Sun-photometer calibration, near-infrared, absorption band, modified Langley method

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1 INTRODUCTION

The Sun-photometer is used to measure the extinction of atmosphere precisely. It is a convenient and portable instrument, and is widely applied in remote sensing of atmospheric compositions and optical properties. Specific wavelengths are selected for specific retrieval purposes. For example, non-absorbed band in visible spectra are normally chosen for aerosol retrieval (Holben, et al., 1998), while 940 nm band is selected for the perceptible water vapor (Bruegge, et al., 1992). Near-infrared bands are adopted to detect larger atmospheric particles such as dust aerosol and cloud, because the radiance in longer wavelength are more sensitive to larger particles (Li, et al., 2009; Kikuchi, et al., 2006). The sun-photometer measurements have been extensively used in modifying radiative transfer models, radiation budget evaluation, and space-borne sensors validations.

One of the most important issues for the atmospheric transmittance measurement is the adequate radiometric calibration of the instrument. It lays the groundwork for the retrieval of other atmosphere optical and physical properties. There are two ways to calibrate the sun-photometer, the Langley plot method and the standard integrating sphere method. The Langley calibration method uses the Sun as a reference light source, assuming that the atmosphere is temporarily invariant during the calibration measurements. By extrapolating the plot of the natural logarithm of the direct solar irradiance $\ln F$ versus the relative optical air mass m to m=0, the calibration constant $\ln F_0$ is derived as the intercept (Shaw, 1976). At present, the Langley calibration is more accurate than the laboratory calibration; it is also lower cost and avoids the data gaps in observations. However, the standard Langley method holds for a limited spectral band, which obeys the Beer-Lambert law. A modified Langley method (MLM) is required for the strongly absorbing bands (Bruegge, et al., 1992). MLM was first proposed by Volz (1974) for the retrieval of column abundance of water vapor from 940 nm water absorption band. This method focused on establishing the relationships between the absorber transmittance and its amount. Studies have proved that MLM calibration gives more accurate calibration constant for the atmosphere absorbing band (such as the 940 nm band) (Halthore, et al., 1997; Bruce, et al., 2001; Han, et al., 1997).

POM02 sky-radiometer is one of the main observation instruments of Skynet, the aerosol-cloud interaction observation Network. It measures at 11 spectral bands, as summarized in Table 1 (Kikuchi, et al., 2006). Measurements made at wavelengths from 400 nm to 1020 nm are used for aerosol retrieval except for the channel at 940 nm, which is used to derive water vapor content. Three near-infrared wavelengths at 1020 nm, 1627 nm, and 2200 nm are designed to retrieve the cloud optical thickness and

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effective particle radius (Kikuchi, et al., 2006). The methods to calibrate the aerosol and water vapor bands are practiced, which are Langley method and MLM, respectively. This study will focus on the investigation of the atmospheric transmittance at the three near-infrared wavelengths, and try to give the proper calibration method.

Table 1 Wavelengths of POM02 Sky-radiometer

Channel	1	2	3	4	5	6	7	8	9	10	11
Wave-length /nm	315	340	380	400	500	675	870	940	1020	1627	2200
FWHM /nm	–	–	–	–	–	–	10	10	10	20	20

2 MODIFIED LANGLEY METHOD

The Langley plot method is based on Beer-Lambert law, in the form of natural logarithm

$$\ln(V/R) = \ln(V_0) - \tau \cdot m \quad (1)$$

where V and V_0 are the instrument signals corresponding to the intensities of solar radiation received at the bottom and top of the atmosphere, respectively. They are proportionate to the intensities received. R is the Earth-Sun distance correction factor. The calibration constant is obtained from the fit of $\ln(V/R)$ versus air mass m, the intercept is $\ln V_0$ and the slope τ yields an effective temporal average value of total optical thickness over the measurement period. τ is the sum of contribution from aerosol, molecules scattering and molecules absorption $\tau_m+\tau_a+\tau_u$. The scattering extinction obeys Beer-Lambert law, but the Beer-Lambert law does not work in regions of strong molecular absorptions, such as the 940 nm sun-photometer channel, where includes a large number of water vapor absorption lines distributed randomly (Qie, et al., 2011). In general, the dependence of transmission on the absorber can be written as (Halthore, et al., 1997)

$$T_u = \exp(-a(m \cdot u)^b) \quad (2)$$

where u is the absorber vertical column abundance. Constants a and b depend on the band wavelength, the width of the filter function, the vertical distribution of atmospheric temperature, pressure and absorber. They can be derived by fitting the relationship of T_u and u that measured or simulated by the radiative transfer model. Then

$$\tau \cdot m \to \tau_s \cdot m + a(m \cdot u)^b$$

By substituting it in Eq.(2), we obtain

$$\ln(V/R) + \tau_s \cdot m = \ln(V_0) - a(m \cdot u)^b \quad (3)$$

where τ_s is the sum of aerosol and Rayleigh optical thickness. The τ_a of absorption band is obtained by interpolation from adjacent scattering wavelengths according to the Angstrom law. By a least squares fit of plot $\ln(V/R)+m\tau_s$ versus m^b in Eq.(3), the parameter V_{0ML} is obtained. The calibration constant V_{0ML} is considered to be more accurate than V_0 for the sun-photometer absorption band compared to the normal-used Langly-Plot method.

3 ATMOSPHERIC TRANSMITTANCE AT THE THREE NEAR-INFRARED CHANNELS

Fig. 1 shows the molecular absorption transmittances for the three near-infrared channels wavelengths at 1020 nm, 1627 nm and 2200 nm along a vertical path through the mid-latitude summer atmosphere, as computed with a combined atmospheric radiative transfer model (CART) (Wei, et al., 2007a; 2007b.) Also the transmittances of 870 nm and 940 nm channels are shown for references, as well-known atmospheric window band and water vapor absorption band. It is shown that the 2200 nm channel includes several obvious absorption lines, while the absorptions in 1020 nm and 1627 nm bands are very weak.

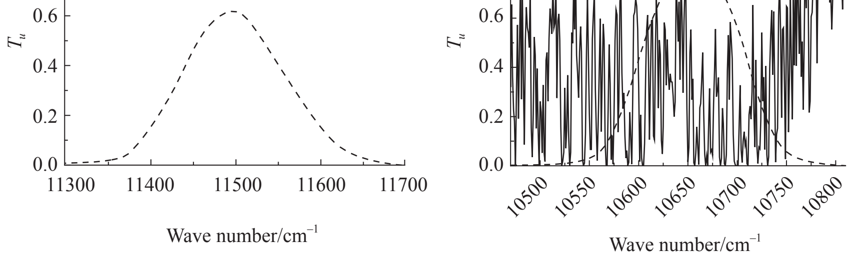
The band weighted atmospheric transmittance is defined as

$$\overline{T} = \frac{\int_{\lambda_1}^{\lambda_2} T(\lambda)\phi(\lambda)\,\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} \phi(\lambda)\,\mathrm{d}\lambda} \quad (4)$$

where $\phi(\lambda)$ is the filter spectral transmission profile, $T(\lambda)$ is the atmosphere spectral transmittance. As the absorption coefficient varies strongly in the channel region, the change of $\phi(\lambda)$ is relatively slow, and the transmission profile for most of filters are nearly rectangular. As a method study in this part, $\phi(\lambda)$ is supposed to be rectangular function, which means that $\phi(\lambda)$ is 1 within the filter band pass, otherwise $\phi(\lambda)=0$.

To study the functional dependence of atmosphere transmission on absorber amount, CART was run to compute the absorber transmittances along a series of slant paths through the mid-latitude summer atmosphere. The solar zenith angles ranged from 0° to 84° (air mass values from 1 to 8.85), with the step of 5°, and 2° when the zenith angle is larger than 50°. The spectral resolution is 1 cm^{-1}, and the spectral range is the same as shown in Table 1.

Fig. 2 and Fig. 3 show the band absorption transmittance as a



(a) 870 nm (b) 940 nm

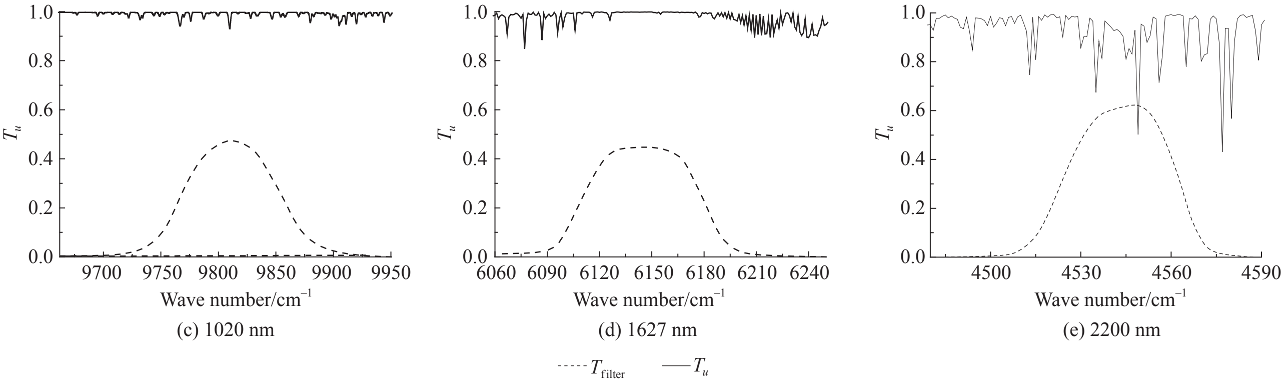


Fig. 1 Molecular absorption transmittances T_u for the mid-latitude summer atmosphere, computed with CART

function of air mass. The least square fitting was made for the plot $\ln(T_u)$ versus m, and the plot $\ln(-\ln T_u)$ versus $\ln(m)$, respectively. The results are shown in Table 2, including the correlation coefficients, intercepts and slopes. As analyzed in part 2, if the relationship between band transmittance and air mass obeys Eq. (1), the plot $\ln(T_u)$–m should be a line crossing the origin. Otherwise, if the relationship obeys Eq.(2), the plot $\ln(-\ln T_u)$–$\ln(m)$ should be a line, and the slope is equal to the parameter b in Eq. (2). As shown in Fig. 2 and Table 2, for the 1020 nm and 1627 nm channels, plotting $\ln(T_u)$–m produced a straight line, and the intercept values were close to zero. It means that the transmittances of these channels well obey the Beer-lambert law. But for the 940 nm and 2200 nm channels, the Beer-lambert law is unsatisfied obviously. The absorption optical thickness varied with the air mass nonlinearly. From Fig. 3 and Table 2, linear fitting of $\ln(-\ln T_u)$–$\ln(m)$ for all the channels are linearly related with improved correlation coefficients, especially for 2200 nm band, and its slope is 0.771. The slopes for the 1020 nm and 1627 nm band are among 1.0±0.1, and the parameter b in Eq. (2) is close to 1. By substituting b in Eq. (2), we obtain Eq. (1).

In conclusion, the traditional Langley method can be used to calibrate the 1020 nm and 1627 nm channel of sun-photometer, as for the 2200 nm channel, a modified Langley method is needed to get more accuracy calibration constant.

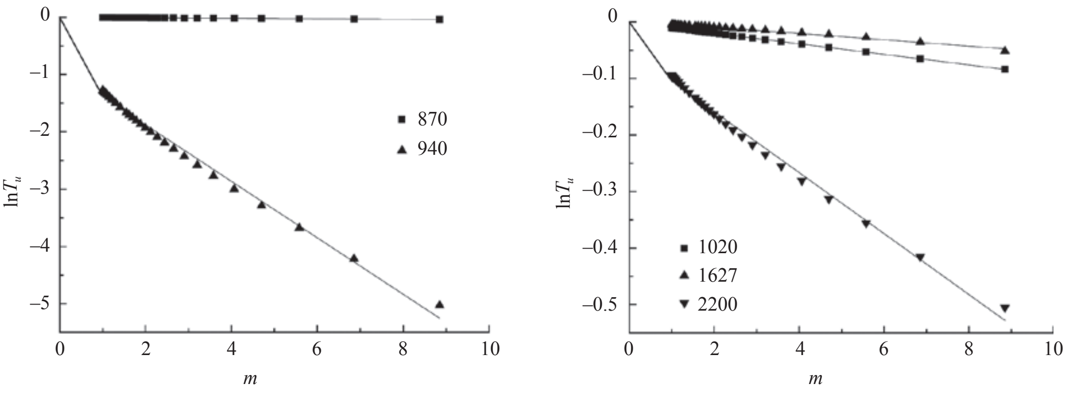


Fig. 2 The band absorption transmittance as a function of air mass, $\ln(T_u)$ versus m, computed by CART

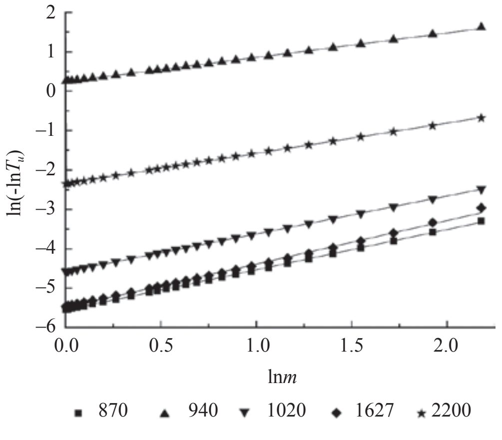


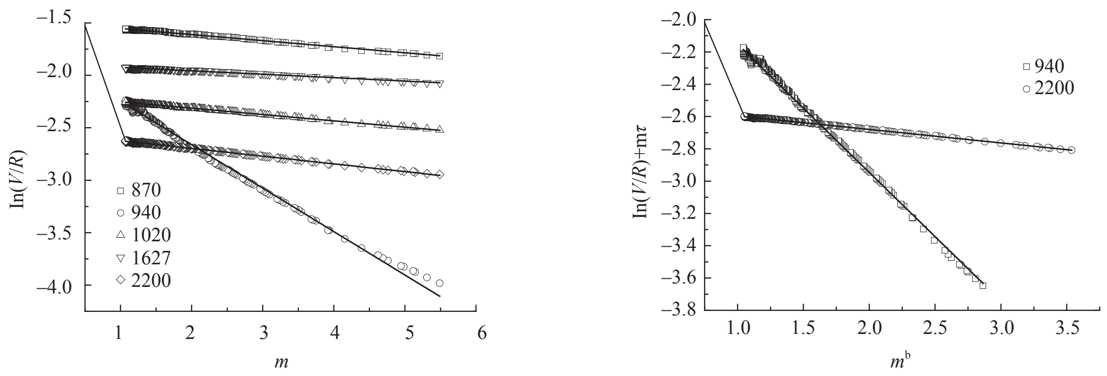
Fig. 3 The band absorption transmittance as a function of air mass, $\ln(-\ln(T_u))$ versus $\ln(m)$, computed by CART

Table 2 The correlation coefficients, intercepts and slopes for fit $\ln(T_u)$–m and $\ln(-\ln T_u)$–$\ln(m)$

Wavelength /nm	Intercept [$\ln(T_u)$–m]	Correlation coefficient [$\ln(T_u)$–m]	Correlation coefficient [$\ln(T_u)$–m]	Slope [$\ln(-\ln T_u)$–$\ln(m)$]
870	4.484E–4	–0.9995	0.99989	1.02281
940	–0.892	–0.99567	0.99977	0.61941
1020	–1.10764E–03	–0.99996	0.99999	0.95982
1627	2.267E–03	–0.99345	0.99877	1.10019
2200	–0.0505	–0.99651	0.99991	0.77061

4 APPLICATION OF THE CALIBRATION METHOD TO THREE NEAR-INFRARED CHANNELS

The Langley calibration requires the total optical thickness to be a constant, which means the atmosphere condition should be highly stable. Observation was performed at Hefei and Xinjiang by POM02 skyradiometer. Only days with clean and stable conditions were selected for the calibration. For the comparison, we used Langley method to calibrate all the channels first, and then calibrated the absorption bands with MLM. The channel transmission was weighted with the filter spectral transmission, and the index b in Eq. (2) was assigned as 0.742 and 0.618 for the 2200 and 940 nm bands, respectively. Fig. 4 shows the calibration of observation data in Xinjing, on August 1st, 2011. Fig 4.(a) and Fig 4.(b) denote the Langley plot for the traditional Langley method and MLM, respectively. It is shown that for the non-absorption bands, plot $\ln(V/R)–m$ is linear ralated, but for the absorption bands, only fit $\ln(V/R)+m\tau_s–m^b$ are linear related. Table 3 shows five groups calibration constants for the two methods. The constant V_{0ML} at 2200 nm band is larger than V_0, which is similar to that of 940 nm band. Correlation coefficients of fit $\ln(V/R)+m\tau_s–m^b$ were better than that of $\ln(V/R)–m$. It proves that the calibration constant is more accurate by using MLM to the 2200 nm channel.



(a) Langley method (b) Modified Langley method

Fig. 4 Langley plot for POM02 skyradiometer(linear fitting was made for the langley plots, shown as the black line)

Table 3 Comparison the calibration constants obtained from Langley and Modified Langley method for the two absorption channels of POM02 skyradiometer("am" and "pm" denote in the morning and afternoon, respectively. "aver" means average of the calibration constants, and σ is the standard deviation)

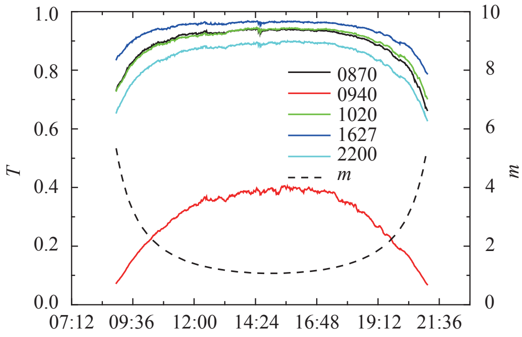
Date	940 nm				2200 nm			
	$V_{0ML}(10^{-3})$	Correlation coefficient	$V_0(10^{-3})$	Correlation coefficient	$V_{0ML}(10^{-4})$	Correlation coefficient	$V_0(10^{-4})$	Correlation coefficient
4.19,pm	0.26297	–0.99912	0.19441	–0.999	0.86124	–0.99807	0.83215	–0.99913
4.25,am	0.25919	–0.99921	0.16977	–0.99912	0.87289	–0.98665	0.83208	–0.99691
8.1,am	0.25762	–0.99872	0.15999	–0.99771	0.81063	–0.99878	0.78097	–0.99845
8.1,pm	0.27136	–0.99734	0.1683	–0.99484	0.83044	–0.99799	0.79871	–0.99717
8.2,pm	0.27745	–0.99864	0.17853	–0.99634	0.84037	–0.99841	0.81071	–0.99533
Aver	0.26572	—	0.1742	—	0.8431	—	0.8109	—
σ/ Aver	2.84%	—	—	—	2.62%	—	—	—
Aver(V_0–V_{0ML})/ Aver(V_{0ML})	34.4%				3.82%			

According to the measurement principle of sun-photometer and theory of error analysis, the error in the measured atmospheric transmittance due to uncertainty in calibration constant can be expressed as

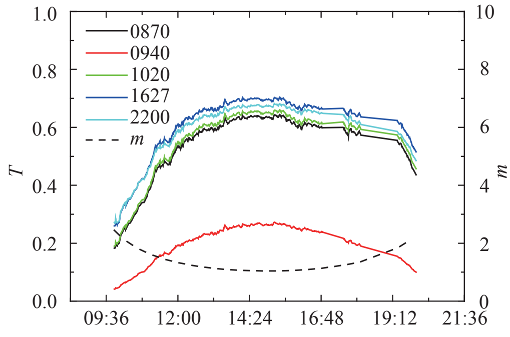
$$dT = -T \cdot \frac{dV_0}{V_0} \tag{5}$$

By substituting the relative deviation of the average calibration constants into Eq. (5), as listed in Table 3, the relative errors of transmittance caused by traditional Langley calibration method for 2200 nm and 940 nm channels were 3.82% and 34.4%, respectively.

Fig. 5 shows the diurnal variations of atmospheric transmittance observed at Xinjiang of China. The sun-photometer was calibrated with Langley method and MLM for non-absorption and absorption channels. The atmosphere was extremely clear on August 1st, 2011, but it is not on July 6th, 2011. Also the diurnal variation of air mass m is shown. As two calibration methods are applied, both the non-absorption and absorption bands transmittances are derived simultaneously. Then several atmosphere compositions can be studied, for example, aerosol, cloud, and other trace gases, which will provide accurate, first-hand data for atmosphere environment research.



(a) August 1st, 2011



(b) July 6th, 2011

Fig. 5 Diurnal variation of atmospheric transmittance retrieved with Langley and Modified Langley method for non-absorption and absorption channels

5 CONCLUSION

The atmospheric transmittance properties for three near-infrared channels of POM02 skyradiometer at the wavelengths of 1020 nm, 1627 nm, and 2200 nm, were studied. It is shown that, the 1020 nm and 1627 nm channels were non-absorption bands, and their transmittances obeyed the Beer-Lambert law. While the 2200 nm channel contained some atmospheric absorption lines, the absorptions at this channel conformed to exponential law. The traditional Langley method can be used to calibrate the 1020 nm and 1627 nm channel of POM02. For the 2200 nm channel, a modified Langley method is needed. Then the 2200 nm channel was calibrated with traditional Langley method and MLM, respectively. The results showed that the accuracy of derived calibration constant can be improved 3.8%, by using MLM, and the measurements accuracy of atmospheric transmittance was improved.

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近红外大气吸收波段太阳辐射计定标

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摘 要：用通用大气辐射传输软件CART模拟了POM02太阳辐射计的1020 nm、1627 nm和2200 nm等3个近红外通道的大气透过率特性。结果表明，前两通道处于大气非吸收波段，其透过率很好的遵从Beer-Lambert定律，而2200 nm通道则有较强的吸收，吸收光学厚度随大气质量的变化服从指数分布，与Beer-Lambert定律有一定的偏差，其定标需采用改进的Langley法。通过选取好天的5个定标实例证明，采用改进的Langley法定标2200 nm通道，可提高其透过率测量精度约3.8%。

关键词：太阳辐射计定标，近红外，吸收波段，改进Langley法

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1 引 言

太阳辐射计是测量大气消光的重要工具，因其测量精度高等优点被广泛用于大气成分及光学性质遥感。根据测量目的的不同，太阳辐射计的测量波段都会经过精心的选择和设计。如探测大气气溶胶，通常选用避开气体分子吸收谱区的可见光波段(Holben 等，1998)；940 nm带正处于水汽吸收区，因而被用于测量水汽含量(Bruegge 等，1992)。近红外波段，因其波长较长，其透过率对气溶胶大粒子、云粒子等更敏感，也被用来探测气溶胶大粒子、云滴谱等(Li 等，2009；Kikuchi 等，2006)。这些测量对改进辐射传输模式、评估辐射收支、定标卫星传感器等研究都有重要意义。

仪器光谱辐射响应的定标精度是影响大气消光测量精度的重要因素。精确定标是精确测量大气成分及其光学和物理性质的前提与基础。太阳辐射计的定标方法主要有两种：Langley法和标准积分球法。Langley法定标是以太阳为光源，假定测量期间大气性质恒定，测得一系列大气质量m时地面接受到的直接辐亮度F，对曲线$\ln F$–m做线性外推，其截距即为定标结果$\ln F_0$(Shaw，1976)。Langley法较积分球法有高精度、耗费低、不间断正常观测等优点。但是，Langley法定标仅适用于透过率遵从Beer-Lambert定律的谱区，对于含有气体分子强吸收线的光谱区域，则需要采用改进的Langley法(Bruegge 等，1992)。改进的Langley法最早由Volz在1974年提出，用于940 nm水汽吸收带反演整层大气可降水量(Volz，1974)。这种方法的关键在于确定吸收气体的透过率与吸收气体含量的关系。国内外的研究表明，在大气吸收波段(如水汽的940 nm波段)采用改进的Langley法能给出更好的定标和反演精度(Halthore 等，1997；Bruce 等，2001；Han 等，1997)。

POM02太阳辐射计是气溶胶-云相互作用观测网Skynet的标准观测仪器之一，共设11个观测波长，其各通道参数见表1(Kikuchi 等，2006)。

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表1 POM02太阳辐射计各通道参数

波段	1	2	3	4	5	6	7	8	9	10	11
中心波长/nm	315	340	380	400	500	675	870	940	1020	1627	2200
带宽/nm	—	—	—	—	—	—	10	10	10	20	20

其中400—1020 nm除940 nm用于测量水汽含量，其余波段都用于气溶胶观测，而1020 nm、1627 nm、2200 nm 等3个近红外波段用于反演水云光学厚度和有效半径(Kikuchi 等，2006)。气溶胶、水汽观测波段的定标方法都已非常成熟，分别采用Langley法和改进的Langley法。本文将通过对3个近红外云反演波段大气透过率的研究，给出适当的定标方法，以便以后进行这3个波段大气透过率的测量。

2 改进的Langley法

Langley法依据Beer-Lambert定律，对等式两边取自然对数

$$\ln(V/R)=\ln(V_0)-\tau\cdot m \tag{1}$$

式中，V和V_0分别表示对应于大气顶和地面直接太阳辐射强度的太阳辐射计输出电压值，它与辐射强度成正比。R为日地距离修正因子。对ln (V/R)与大气质量m做线性拟合，由截距可求得仪器定标系数V_0，其斜率τ为测量期间平均光学厚度，是分子散射、气溶胶散射及分子吸收光学厚度之和$\tau_m+\tau_a+\tau_u$。τ的散射部分(分子和气溶胶散射)遵从Beer-Lambert定律；而吸收部分，尤其是分子强吸收波段，太阳辐射计在很窄的通道带宽内通常包含有多条强弱不等的吸收线，Beer-Lambert定律不再成立，如940 nm波段(Qie 等，2011)。分子吸收透过率可表示为(Halthore 等，1997)：

$$T_u=\exp(-a(m\cdot u)^b) \tag{2}$$

式中，u为吸收气体含量；a、b为常数，它们的值依赖于波长、带宽和大气温度、压强、吸收气体分布廓线，可通过实际测量的大气透过率与吸收气体含量或辐射传输算法模拟的二者关系得到。则式(1)最后一项转换为

$$\tau\cdot m\rightarrow\tau_s\cdot m+a(m\cdot u)^b$$

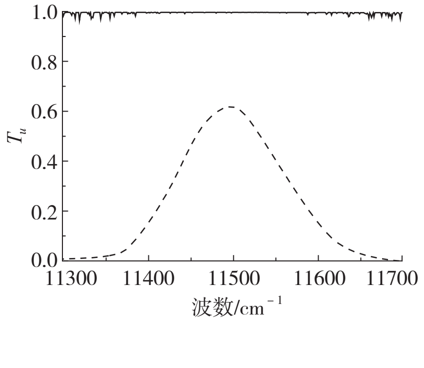
代入式(1)得到

$$\ln(V/R)+\tau_s\cdot m=\ln(V_0)-a(m\cdot u)^b \tag{3}$$

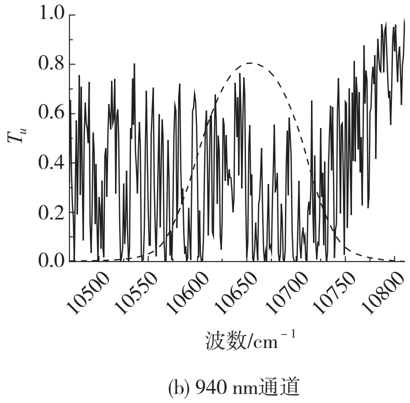
式中，τ_s表示分子与气溶胶散射光学厚度之和，吸收波段的气溶胶光学厚度τ_a可由邻近的几个非吸收波段的τ_a根据Angstrom公式插值得到。类似地，将等式左边$\ln(V/R)+m\tau_s$对m^b在坐标系上描点，并对其做线性拟合，即得到改进的Langley法的定标系数，标记为V_{0ML}。在吸收波段，改进Langley法可得到更精确的定标系数。

3 3个近红外通道的大气透过率

图1为用中国科学院安徽光学精密机械研究所研制的通用大气辐射传输软件CART(Wei 等，2007a；Wei 等，2007b)计算的中纬度夏季大气模式在1020 nm、1627 nm、2200 nm 等3通道的分子吸收光谱透过率。870和940 nm通道分别作为典型的大气窗口通道和水汽吸收通道也画在图中作为参考。从图中可以看出，2200 nm通道有着较强吸收谱线，1020 nm、1627 nm波段仅有少量很弱的吸收线。



(a) 870 nm通道



(b) 940 nm通道

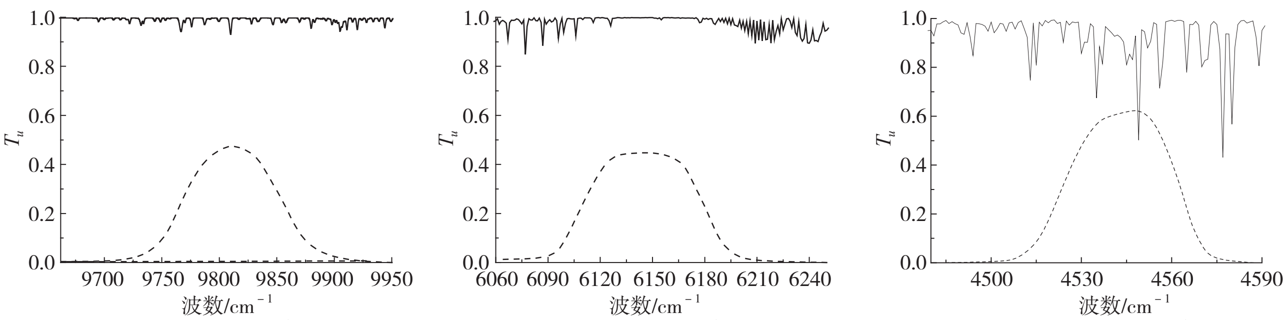


图1　CART计算的中纬度夏季大气模式整层大气分子吸收光谱透过率T_u及POM02 太阳辐射计各通道光谱响应曲线T_{filter}

某一通道的大气平均透过率(即通道透过率)定义为

$$\bar{T}=\frac{\int_{\lambda_1}^{\lambda_2}T(\lambda)\phi(\lambda)\,\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2}\phi(\lambda)\,\mathrm{d}\lambda} \tag{4}$$

式中，$\phi(\lambda)$为太阳辐射计滤光片的光谱透过率函数，$T(\lambda)$为大气光谱透过率。因为相对于通道内光谱吸收线导致的吸收系数急剧变化，仪器滤光片透过率的变化是慢变的，且多数滤光片的通透曲线可近似为矩形。该部分作为方法研究，暂假设$\phi(\lambda)$为矩形函数，即在滤光片带通范围内假定$\phi(\lambda)=1$，其他波长处透过率为0。

为研究不同吸收气体含量时各通道的大气透过率，本文以中纬度夏季大气模式为例，用CART软件计算了不同太阳天顶角下大气分子吸收的平均透过率。计算中，太阳天顶角变化范围为0°—84° (大气质量变化范围：1—8.85)，天顶角小于和大于50°时，步长分别取为5° 和2° 。光谱分辨率为1 cm^{-1}，带宽如表1。

图2、图3分别是算得的各通道吸收气体平均透过率(为简洁，以下文中平均透过率标记都省略平均值符号)与大气质量关系：$\ln(T_u)-m$与$\ln(-\ln T_u)-\ln(m)$，并对两关系都做了线性拟合。表2给出两种线性拟合的相关系数、截距和斜率。由第2节的分析可知，若气体吸收透过率T_u近似满足式(1)，则$\ln(T_u)-m$曲线应是一条过原点的直线。而若T_u近似满足式(2)，则$\ln(-\ln T_u)-\ln(m)$曲线应是一条直线，斜率即式(2)中的指数b。从图2和表2可以看出，1020 nm和1627 nm通道与870 nm类似，几乎完全满足$\ln(T_u)-m$过原点、线性关系，即很好的遵从Beer-Lambert定律；而940 nm和2200 nm波段，显然背离这一关系，整层大气的光学厚度随大气质量变化并非线性关系。从图3和表2可知，所有通道$\ln(-\ln T_u)-\ln(m)$线性拟合都有极好的相关性，2200 nm线性相关系数提高尤为明显，其拟合线斜率为0.771。1627 nm与1020 nm通道拟合线的斜率都在1.0 ± 0.1以内，即指数b接近1，式(2)退化为基本满足式(1)。

综上，太阳辐射计1020 nm、1627 nm通道定标可采用Langley法，而2200 nm则需要采用改进的Langley法才能得到较高的定标精度。

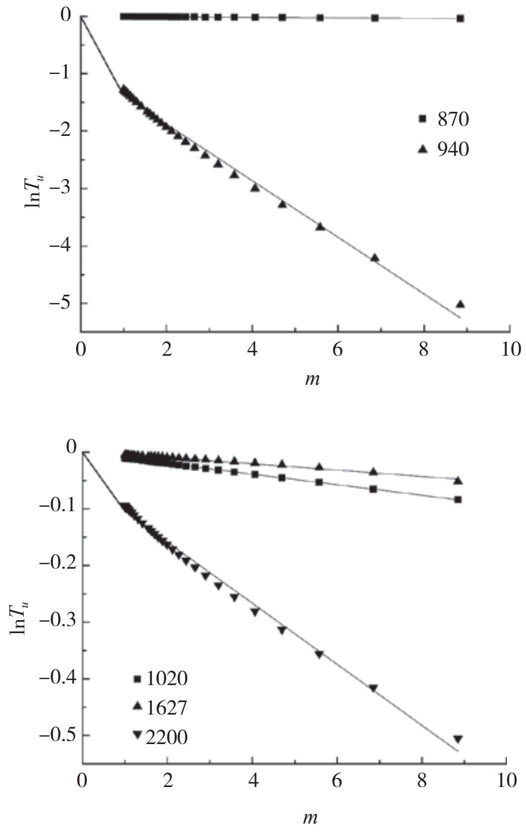


图2　CART计算的各通道吸收气体平均透过率与大气质量关系(黑色直线为对两者的线性拟合)

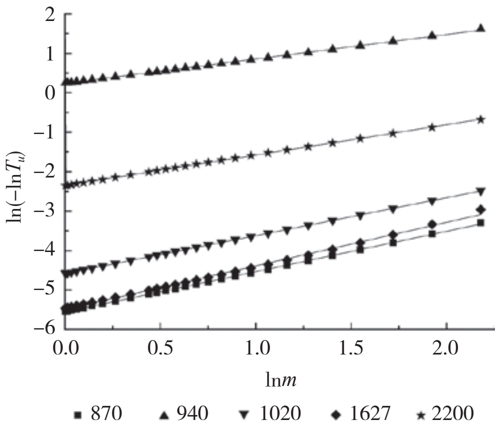


图3 CART计算的各通道的平均透过率与大气质量的关系，图中黑色直线为对两者的线性拟合

表2 $\ln(T_u)$–m与$\ln(-\ln T_u)$–$\ln(m)$线性拟合相关系数、截距和斜率

波段/nm	截距 $[\ln(T_u)$–$m]$	线性相关系数 $[\ln(T_u)$–$m]$	线性相关系数 $[\ln(-\ln T_u)$–$\ln(m)]$	斜率 $[\ln(-\ln T_u)$–$\ln(m)]$
870	4.484E − 4	− 0.9995	0.99989	1.02281
940	− 0.892	− 0.99567	0.99977	0.61941
1020	− 1.10764E − 03	− 0.99996	0.99999	0.95982
1627	2.267E − 03	− 0.99345	0.99877	1.10019
2200	− 0.0505	− 0.99651	0.99991	0.77061

4 3个近红外通道定标实例

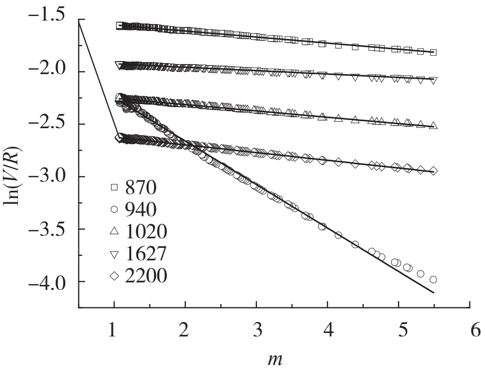
太阳辐射计的Langley法定标要求观测期间整层大气光学厚度是一个常数，即要求大气状况相对稳定。用POM02太阳辐射计在合肥、新疆两地分别做了观测，选择大气晴朗、清洁、稳定的好天的数据进行定标。为比较，先对所有波段都采用Langley法定标，然后对吸收通道进行了改进的Langley法定标。对式(4)中的平均透过率考虑仪器的滤光片通透特性，得到中纬度夏季大气模式2200 nm与940 nm通道b值分别为：0.742和0.618。图4为2011年8月1日上午在新疆观测数据的定标实例。由图4可见，非吸收波段其曲线$\ln(V/R)$–m都有很好的线性关系，而吸收波段尤其是吸收较强的940 nm通道只有曲线$\ln(V/R)+m\tau_s-m^b$有很好的线性相关性。表3列出了5组吸收通道分别用两种方法定标的结果。由表3可知，2200 nm通道的改进Langley法定标结果较Langley法大，即$V_{0ML}>V_0$，这与940 nm通道情况类似；且通常曲线$\ln(V/R)+m\tau_s-m^b$较$\ln(V/R)$–m有更好的线性相关性。这也说明2200 nm通道采用改进Langley法能得到更精确定标结果。

根据太阳辐射计测量原理及误差分析理论，可得某波段定标值误差对其透过率反演精度的影响如下

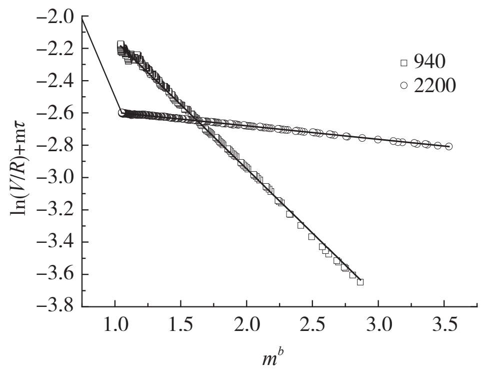
$$\mathrm{d}T=-T\cdot\frac{\mathrm{d}V_0}{V_0} \tag{5}$$

从而由两种方法定标平均结果的相对偏差，如表3最后一行，可估算得2200 nm与940 nm通道采用常规的Langley法定标将分别带来3.82%和34.4%的误差。

如图5所示给出了对太阳辐射计的吸收和非吸收波段分别采用Langley法和改进的Langley法定标后，



(a) Langley法

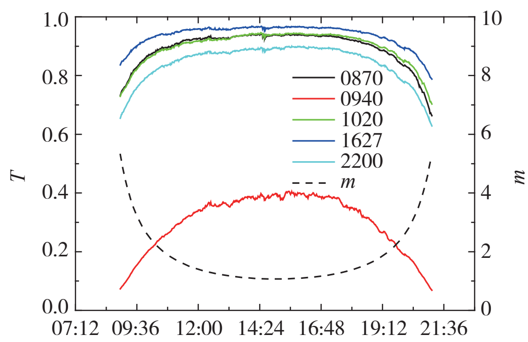


(b) 改进的Langley法

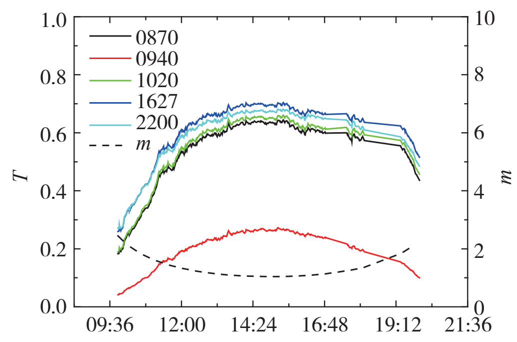
图4 POM02太阳辐射计定标Langley图(黑色直线为对各通道Langley点的线性拟合)

表3 POM02太阳辐射计两吸收通道分别采用Langley法和改进的Langley法定标结果比较
(am、pm分别表示上午和下午，Aver和σ表示这几组定标结果的平均值和标准差)

日期	940 nm				2200 nm			
	$V_{0ML}(10^{-3})$	线性相关系数	$V_0(10^{-3})$	线性相关系数	$V_{0ML}(10^{-4})$	线性相关系数	$V_0(10^{-4})$	线性相关系数
4.19,pm	0.26297	−0.99912	0.19441	−0.999	0.86124	−0.99807	0.83215	−0.99913
4.25,am	0.25919	−0.99921	0.16977	−0.99912	0.87289	−0.98665	0.83208	−0.99691
8.1,am	0.25762	−0.99872	0.15999	−0.99771	0.81063	−0.99878	0.78097	−0.99845
8.1,pm	0.27136	−0.99734	0.1683	−0.99484	0.83044	−0.99799	0.79871	−0.99717
8.2,pm	0.27745	−0.99864	0.17853	−0.99634	0.84037	−0.99841	0.81071	−0.99533
Aver	0.26572	—	0.1742	—	0.8431	—	0.8109	—
σ / Aver	2.84%	—	—	—	2.62%	—	—	—
$\mathrm{Aver}(V_0-V_{0ML})/\mathrm{Aver}(V_{0ML})$	34.4%				3.82%			



(a) 2011年8月1日



(b) 2011年7月6日

图5 采用Langley和改进的Langley法测量大气斜程透过率日变化举例

测量得到的新疆晴好天气2011年8月1日与大气清洁度较差天气2011年7月6日两天的整层大气斜程透过率日变化情况，同时画出了大气质量m随时间变化图。图中展示了采用两种方法定标，可同时得到吸收波段和非吸收波段的大气透过率，可同时关注气溶胶、云和微量气体成分引起的大气透明度的变化，这为研究大气环境变化提供较高精度的测量数据。

5 结 论

本文通过对POM02太阳辐射计3个近红外通道1020 nm、1627 nm和2200 nm大气透过率的研究，发现1020 nm与1627 nm通道几乎没有吸收，其透过率满足Beer-Lambert定律，而2200 nm通道内有较多的吸收线，其光学厚度随大气质量的变化不服从Beer-Lambert定律，但服从指数分布。因此，POM02的1020 nm、1627 nm两通道定标采用Langley法即可，而2200 nm通道定标则需通过改进的Langley法。通过对2200 nm通道两种方法定标结果的对比得到，在该波段采用改进Langley法定标将使太阳辐射计定标精度提高约3.8%，显著地提高大气透过率的测量精度。

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