Spectral information retrieval from integrated broadband photodiode Martian ultraviolet measurements

Luis Vázquez,[1,2] María-Paz Zorzano,[2,*] and Salvador Jimenez[3]

[1]*Departamento de Matemática Aplicada, Facultad de Informática, Universidad Complutense de Madrid, 28040 Madrid, Spain*
[2]*Centro de Astrobiología (CSIC-INTA), Carretera de Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, Spain*
[3]*Departamento de Matemática Aplicada a las TT.II., E.T.S.I.T., Universidad Politécnica de Madrid, 28040 Madrid, Spain*
Corresponding author: zorzanomm@inta.es

We propose an algorithm to retrieve the global features of the spectral dependence of the ultraviolet (UV) irradiance from integrated, broadband UV measurements performed with a set of photodiodes with different UV filters. This fit, when applied to ground-based measurements and compared with the incident Solar spectral irradiance on the top of the atmosphere, may be used to extract the spectral dependence of the UV opacity and the most relevant parameters characterizing the scattering with atmospheric aerosol (Angstrom exponent, etc.) as well as the biological effective doses. In this way, using a set of photodiodes instead of a spectrophotometer, one may get spectral information within very low mass, package, and weight constraints, which is particularly useful for space missions. We consider its application for the rover-based exploration of the Martian ground, which is subject to daily and seasonal opacity variations. © 2007 Optical Society of America

OCIS codes: 280.1100, 290.4020, 040.7190, 120.0120.

In this Letter we describe a general purpose algorithm to retrieve the global features of the spectral dependence of the UV irradiance in the 200–400 nm range, using the integrated signal of five different UV broadband photodiodes. Although this algorithm is of particular interest for the future ground-based exploration of Mars, it may be applicable to other situations where low-cost (in terms of mass, weight, etc.) spectral UV irradiance measurements are required. To date there are no *in situ* measurements of the UV levels on the Martian ground surface. However the future Mars Science Laboratory (MSL) mission to Mars, NASA 2009, will include a light UV photodiode suite in the Rover Environmental Monitoring Station (REMS) sensor, which will monitor the daily and seasonal variations of the UV ground level irradiance. The five photodiodes are here named UV-C (208–280 nm), UV-B (280–320 nm), UV-A (320–400 nm), UV-D (245–290 nm), and UV-E (310–335 nm). The size of each photodiode will be smaller than 5 mm in diameter and 2 mm height. Each one will weight about 2 g. The photodiodes will be placed on the rover deck, facing the sky, and thus measuring the total Sun irradiance I_{total}, which includes both the direct Sun irradiance I_{dir} (i.e., the solar radiation arriving at the ground in the direction of the Sun) and the diffuse component I_{diff}. The rover mast may block the direct Sun irradiance when a shadowing event is programmed and only the diffuse irradiance is measured. The accuracy of this sensor will be limited mostly by the degradation due to the slow deposition of atmospheric dust and the callibration of the sensor degradation by means of image processing. In REMS there will be an extra UV photodiode measuring the whole UV interval (200–400 nm), which may be used for redundancy checks. Photodiodes have the advantage of being cheap, small in size, and light, and have been proved to be very stable under temperature variations, long-term operation, and high UV doses. The disadvantage of this system is that the photodiode gives an integrated measurement over a certain bandwidth instead of the spectral information that is often desired but that would require the use of an spectrophotometer (between 200 g and 1 kg weight and dimensions of the order of several decimeters). This is a general problem in space mission instrumentation when the weight, packaging, energy, and data budget are severely constrained, and adapted algorithms need to be implemented to extract scientifically relevant information. To illustrate the way the algorithm works, we use a numerically obtained UV spectral irradiance, from a radiative transfer code [1], for a realistic operation scheme [2] and estimate, among other things, the resulting UV I_{dir} and I_{diff} spectral irradiances at the ground. We include the latest results on dust and cloud vertical distribution and Angstrom exponent [3], O_3 measurements from SPICAM on board the Mars Express satellite, and the measured visible opacities of the ground-based MER rovers [4,5] as well as the UV ground albedo as seen by Mars Express [6], aerosol UV scattering properties, and the known solar incident irradiance at the top of the atmosphere, $I_{solar}(\lambda)$ [7], for a particular example. The characteristic Martian micrometer-sized red dust is blown into the sky by winds (dust devils, dust plumes) and dust storms. The aerosol content is generally described by the opacity $\tau(\lambda)=$

$-\ln[I_{dir}(\lambda)/I_{solar}(\lambda)]$ at a given wavelength. Here $I_{solar}(\lambda)$ is the incident radiation at the top of the atmosphere. Monitoring the daily and seasonal variations of this function, one can describe the dust circulation and settling processes and estimate the absorption properties of dust. The spectral dependence of the aerosol optical depth can be characterized by Angstrom's turbidity expression $\tau = \beta/\lambda^{\alpha}$, where α is the so-called Angstrom exponent and is related to the aerosol size and β is the turbidity parameter and defines the aerosol optical depth at $1\ \mu m$. Knowing $I_{solar}(\lambda)$, we have evaluated $I_{dir}(\lambda)$ and $I_{diff}(\lambda)$ spectral irradiances at the ground as they would be measured *in situ* at noon, at equatorial locations when Mars is at mean Sun–Mars distance (1.52 AU), when the atmospheric pressure is 6 mbars, the O_3 level is $3\ \mu m$ atm, in a "clear" dust scenario [2]. However, as mentioned above, these spectrally resolved measurements will not be available. We will know instead the integral outputs from five photodiodes, in our particular test case: $C_k = \int_{\lambda_{k-1}}^{\lambda_k} I(\lambda)d\lambda$, $k = 2, 3, 4$, with $\lambda_1 = 208$ nm (the UV irradiance below 208 nm is strongly absorbed by the atmospheric CO_2), $\lambda_2 = 280$ nm, $\lambda_3 = 320$ nm, and $\lambda_4 = 400$ nm, together with $A = \int_{\mu_1}^{\mu_2} I(\lambda)d\lambda$, $B = \int_{\mu_3}^{\mu_4} I(\lambda)d\lambda$, and $\mu_1 = 245$ nm, $\mu_2 = 290$ nm, $\mu_3 = 310$ nm, $\mu_4 = 355$ nm. In general, the sensors' output will be an integral of the convoluted function $I(\lambda) = I^*(\lambda)g(\lambda)$,

Fig. 1.   (Color online) Top, Real signal $I_{dir}(\lambda)$, interpolating polynomial $Q(\lambda)$, and rational function $R(\lambda)$. Bottom, The linear combination $aQ(\lambda) + bR(\lambda)$ with $a + b = 1$ and $a = 0.77$ is indeed a soft interpolation of the direct spectral irradiance on the ground.

where $I^*(\lambda)$ is the incident radiation on top of the filter and $g(\lambda)$ is a previously calibrated and thus known (filter + detector) response function. Here for simplicity and without loss of generality we assume $g(\lambda) = 1$ within the photodiode interval and 0 outside. We want to recover a primitive function $f(\lambda) = \int_{\lambda_1}^{\lambda} I(x)dx$ satisfying the following conditions: $f(\lambda_1) = 0$, $f(\lambda_k) = C_k$ with $k = 2, 3, 4$, $f(\mu_2) - f(\mu_1) = A$, and $f(\mu_4) - f(\mu_3) = B$. In this interpolation problem we will construct a polynomial $P(\lambda)$ of fifth degree (since we have six conditions) that satisfies these conditions and such that the function $I(\lambda)$ can be approximated by its derivative $Q(\lambda) = dP(\lambda)/d\lambda$. Let P be $P(\lambda) = a(\lambda - \lambda_1)^5 + b(\lambda - \lambda_1)^4 + c(\lambda - \lambda_1)^3 + d(\lambda - \lambda_1)^2 + e(\lambda - \lambda_1)$. The unknown coefficients are obtained from

$$\begin{pmatrix} a \\ b \\ c \\ d \\ e \end{pmatrix} = M^{-1} \begin{pmatrix} C_2 \\ C_3 \\ C_4 \\ A \\ B \end{pmatrix},$$

where the matrix M is given by

$$M = \begin{pmatrix} l^5 & l^4 & l^3 & l^2 & l \\ m^5 & m^4 & m^3 & m^2 & m \\ n^5 & n^4 & n^3 & n^2 & n \\ o^5 - p^5 & o^4 - p^4 & o^3 - p^3 & o^2 - p^2 & o - p \\ q^5 - r^5 & q^4 - r^4 & q^3 - r^3 & q^2 - r^2 & q - r \end{pmatrix},$$

with $l = (\lambda_2 - \lambda_1)$, $m = (\lambda_3 - \lambda_1)$, $n = (\lambda_4 - \lambda_1)$, $o = (\mu_2 - \lambda_1)$, $p = (\mu_1 - \lambda_1)$, $q = (\mu_4 - \lambda_1)$, and $r = (\mu_3 - \lambda_1)$. As will be shown below, and for the photodiode ranges chosen, this approximation works well on the higher range of the UV interval. We combine it with a rational interpolation that works well on the lower range of the UV interval, namely, $S(\lambda) = P_1(\lambda)/P_2(\lambda)$, such that $I(\lambda)$ is approximated by $R(\lambda) = dS(\lambda)/d\lambda$. Having six conditions to be satisfied, we must stipulate that the degrees of the polynomial functions P_1 and P_2 should sum to 4 (and that none of the polynomials will be equal to zero) [8]. If we ignore the rational functions that have a singularity in the range $[\lambda_1, \lambda_4]$ and those that become negative, the only option is that of P_1 being a polynomial of degree 1 and P_2 a polynomial of degree 3. In Fig. 1, top, we show the approximation to $I_{dir}(\lambda)$, which is obtained from $R(\lambda)$ for $\lambda < 300$ nm and $Q(\lambda)$ for $\lambda > 300$ nm. This interpolation deviates strongly on the UV-A range. We can use a linear combination of the two functions $aQ(\lambda) + bR(\lambda)$ such that $a + b = 1$ and a is taken so as to minimize the integral over the range $[\lambda_1, \lambda_4]$ of the square of the fit. This is shown in Fig. 1, bottom, for $a = 0.77$, where the characteristic peaks of the solar emission are softened and the general trend is preserved. Next we apply the same procedure to obtain the interpolated functions of the incoming solar spectral irradiance $I_{solar}(\lambda)$ and evaluate the approximated functions $Q_{top}(\lambda)$ and $R_{top}(\lambda)$. By doing this we can obtain the
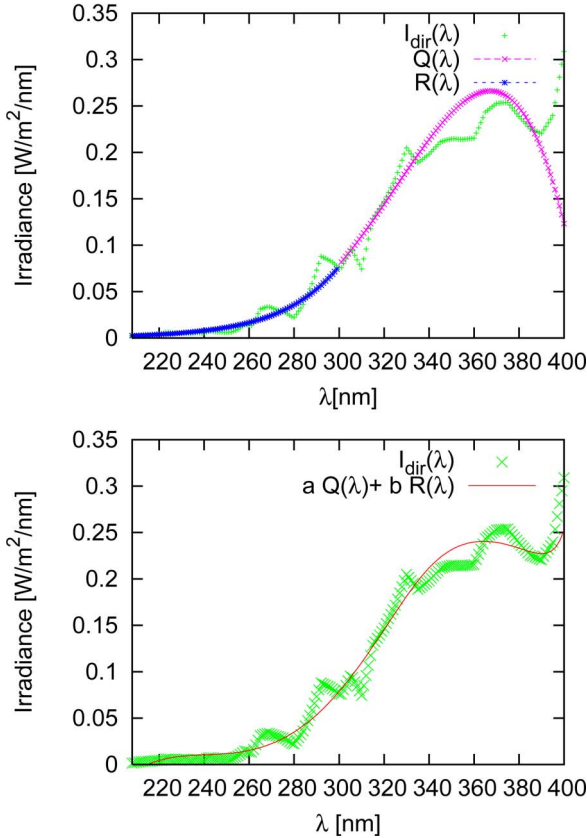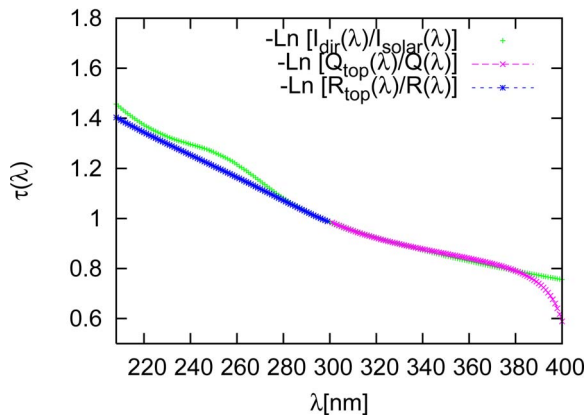
Fig. 2. (Color online) Comparison of the retrieved $\tau(\lambda)$ from the interpolated signal with the real one. The difference in the 250 nm range is the signature of ozone absorption.
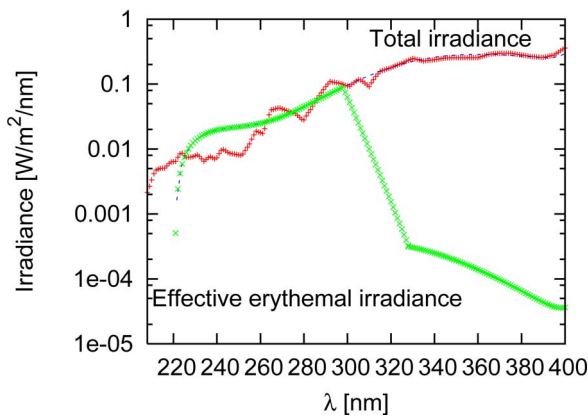

Fig. 3. (Color online) Total UV irradiance on the Martian surface and retrieved interpolated function convoluted with the CIE action spectrum.

approximation of the opacity from either interpolating function, $-\ln Q_{top}(\lambda)/Q(\lambda)$ or $-\ln R_{top}(\lambda)/R(\lambda)$, and compare with the real opacity, $-\ln I_{solar}(\lambda)/I_{dir}(\lambda)$. As is shown in Fig. 2, the result is coincident in the intermediate range and good enough to extract, in addition to the spectral capacity, the Angstrom coefficient α, which in this case turns out to be $\alpha \approx 1$. The difference in the 250 nm range is the signature of ozone absorption.

Finally, the total irradiance incident on a normal surface is $I_{total}=I_{dir}+I_{diff}$. The instantaneous (per second) biologically weighted dose is defined as $D = \int I_{total}(\lambda)B(\lambda)d\lambda$. In general, $B(\lambda)$ characterizes the spectral sensitivity or biological response of an organism or biological structure (such as the one for DNA, or uracil, or specific proteins, or skin) to UV radiation. For a nice study of Martian Biological Effective Doses for T7 and Uracil, see [9]. For instance, the

CIE action spectrum for the susceptibility of the Caucasian skin to sunburn is $B(\lambda)=1\lambda<298$ nm, $B(\lambda)=10^{0.094(298-\lambda)} \times 298$ nm $< \lambda < 328$ nm, $B(\lambda) =10^{0.015(139-\lambda)} \times 328$ nm $< \lambda < 400$ nm. The multiplication of the irradiance times the CIE action spectrum gives the effective erythemal irradiance, and its integral over the UV spectral range is the widely used UV Index (UVI). In Fig. 3 we show the total irradiance, its interpolating function as retrieved from the five photodiodes, and the multiplication of the interpolation by the CIE action spectrum; the area below the effective erythemal irradiance spectrum is the UVI, in this case 2.76 for the interpolating function and 2.88 for the real total irradiance.

References

1. M.-P. Zorzano, A.-M. Mancho, and L. Vazquez, Appl. Math. Comput. **164**, 263 (2005).
2. M.-P. Zorzano and C. Cordoba-Jabonero, "Influence of aerosol multiple scattering of ultraviolet radiation on Martian atmospheric sensing," Icarus (to be published).
3. F. Montmessin, E. Qumerais, J. L. Bertaux, O. Korablev, P. Rannou, and S. Lebonnois, J. Geophys. Res. **111**, E12S06 (2006).
4. M. T. Lemmon, M. J. Wolff, M. D. Smith, R. T. Clancy, D. Banfield, G. A. Landis, A. Ghosh, P. H. Smith, N. Spanovich, B. Whitney, P. Whelley, R. Greeley, S. Thompson, J. F. Bell III, and S. W. Squyres, Science **306**, 1753 (2004).
5. M. D. Smith, M. D. Greenbelt, M. J. Wolff, R. T. Clancy, N. Spanovich, D. Banfield, A. Ghosh, and the Athena Science Team, in *Second Workshop on Mars Atmosphere Modelling and Observations*, F. Forget, M. A. Lopez-Valverde, M. C. Desjean, J. P. Huot, F. Lefevre, S. Lebonnois, S. R. Lewis, E. Millour, P. L. Read, and R. J. Wilson, eds. (LMD, IAA, AOPP, CNES, ESA, 2006), p. 133.
6. S. Perrier, J. L. Bertaux, F. Lefvre, S. Lebonnois, O. Korablev, A. Fedorova, and F. Montmessin, J. Geophys. Res. **111**, E09S06 (2006).
7. G. Thuillier, M. Hersé, D. Labs, T. Foujols, W. Peetermans, D. Gillotay, P. C. Simon, and H. Mandel, Sol. Phys. **214**, 1 (2003).
8. J. Stoer and R. Burlisch, *Introdution to Numerical Analysis*, 2nd ed. (Springer-Verlag, 1993).
9. M. R. Patel, A. Brces, T. Kerkgyrt, Gy. Ront, H. Lammer, and J. C. Zarnecki, Adv. Space Res. **33**, 1247 (2004).