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A new approach for limb darkening correction on Venus nightside infrared images

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Abstract. We define limb darkening (LD) as the decrease of the radiance that emerges from a planetary atmosphere at increasing emergence angle (i.e. angle between direction of observation and surface normal). The effect is caused by the larger atmospheric column depth (i.e. emergence angle) crossed by radiation (coming from surface or lower atmosphere) observed at larger emergence angle. LD correction consists in retrieving radiance that would be observed at emergence angle equal to zero.
In this work a LD correction is applied on Venus nightside infrared images. The reasons that led to choose this planet are the very important role played by its atmosphere (very dense and opaque) and the huge amount of new spectroscopic data furnished by the VIRTIS instrument, mounted on Venus Express spacecraft, that is currently orbiting the planet.
Our approach on LD correction is based on statistics of observed data, instead of synthetic models, as in previous works. We obtained linear relations between radiances emerging from atmosphere at five different wavelengths (1.03 μm, 1.31 μm, 1.74 μm, 2.30 μm and 3.71 μm) and emergence angle. Our results agree with previous works. In addition, a link between the parameters of the linear relations and height where emission is originated from has been found. This link can be explained remembering that radiation coming from the upper atmospheric layers is less attenuated than radiation originated in the lower ones.

Key words. limb darkening – Venus – infrared – airmass – emergence angle

1. Introduction

In satellite observations, it is important to take into account the LD effect, i.e. the radiance loss at increasing emergence angle (i.e. angle between the surface normal and direction of observation). This effect arises because radiation coming from surface or lower atmosphere and observed at higher emergence angles traverses a larger air mass, and hence is more attenuated and/or scattered, than that coming from the atmospheric upper layers.
A LD study is useful to:

- give qualitative information about atmospheric opacity and/or density: the faster

the radiance decreases with emergence angle, the optically thicker the atmosphere;
- understand if the atmospheric model used is appropriate: this can be made by comparing the observed and synthetic behaviours of radiance emerging from the atmosphere (hereon I) with emergence angle (θ);
- have a better data reduction: without taking into account this effect, areas on the planet observed at different emergence angle with equivalent thermal energy, would appear as different emitters;

We chose to study LD on Venus for three main reasons:

- the atmosphere here plays a more important role than on other planets, being very opaque and dense;
- there is a huge amount of new spectroscopic data coming from the VIRTIS instrument, mounted on the Venus Express spacecraft, that is presently orbiting the planet.
- previous studies on Venus LD have been already developed (Carlson et al. 1993; Grinspoon et al. 1993) and hence a comparison between our results and the previous ones can be performed.

The analysis is realised using data coming from the infrared channel of VEX-VIRTIS (Piccioni et al. 2007): it works in the Near InfraRed (NIR,1-5 μm), a spectral region of particular interest because it corresponds to thermal emission peak of Venus surface, it is characterised by a high opacity and it contains the H_2O and CO_2 absorption bands (Pollack et al. 1993).

Only Venus nightside data have been considered, because in the dayside LD is less prominent as the solar radiation is reflected by the upper layers of the atmosphere (Moroz et al. 1985; Titov et al. 2007) resulting less attenuated.

The aim of this work is to retrieve a relation between I and θ, obtaining the radiance that would be measured for every pixel in a nadir observation (i.e. the LD corrected radiance value).

Radiances from five different wavelengths are considered for this study: one (1.03 μm) is mainly composed by surface emission, whereas the other four (1.31 μm, 1.74 μm, 2.30 μm and 3.71 μm) are characterised by atmospheric emission originated at different heights (0-25 km, 15-35 km, 25-40 km and 60-70 km respectively) (Meadows & Crisp 1996; Grinspoon et al. 1993; Tsang et al. 2008).

2. Data reduction

360 VIRTIS images (acquired from April 2006 to February 2007), corresponding to about 4 millions spectra, were selected for this work. Prior to apply the LD correction, some preliminary operations were fulfilled.

2.1. Wavelength shift refining

A slight spectral shift (roughly 10 nanometers) between VIRTIS and synthetic spectra has been observed. This effect can be linked to instrument temperature variations during the acquisition, since the relation between dispersion axis of focal plane and wavelength depends on this temperature.

To correct this effect, the positions and FWHM of the 1.03 μm, 1.10 μm and 1.31 μm bands in synthetic and observed spectra have been found and an average shift has been calculated.

2.2. Scattered sunlight correction

Although we are observing the planet nightside, scattered solar light can be present. To eliminate diffuse solar light, radiance at 1.05 μm is considered. In fact, according to synthetic data by (Tsang et al. 2008), radiance is expected to be zero at this wavelength the ”residual radiance” at 1.05 μm has been attributed to solar light. Propagating this residual radiance value over the whole spectrum, according to the Rayleigh law (i.e. intensity of diffuse light scales as $\lambda \propto -4$, where λ is wavelength), the scattered sunlight spectrum was obtained and eliminated.

3. Work procedure

We started from Radiative Transfer Equation: $\cos\theta\frac{dI_\lambda}{d\tau_\lambda} = S_\lambda - I_\lambda$ (where θ is the emergence angle, I_λ is the radiance emerging from the atmosphere at wavelength λ, τ is the optical depth and S is the source function), that we solved applying Eddington approximation, according to which:

$$I_\lambda = A_\lambda + B_\lambda \cos\theta \quad (1)$$

Hence, a linear relation between I and $\cos\theta$ exists. Once computed A_λ and B_λ parameters, the radiance that every point would have if observed from nadir ($\cos\theta = 1$), that is LD corrected radiance value, can be retrieved. However, at fixed wavelength, A_λ and B_λ are not constant, but vary with optical depth and, if the emission comes from the surface, also with the surface emission (i.e. surface temperature and surface emissivity).

These parameters have been obtained by means of a statistical analysis on the VIRTIS dataset used.

3.1. Limb darkening correction at 1.31 μm, 1.74 μm, 2.30 μm and 3.71 μm

For atmospheric radiation, A_λ and B_λ coefficients depend on optical depth, hence on atmospheric coverage. Accordingly to our hypothesis, by analysing the plots I vs $\cos\theta$, data with the same atmospheric coverage should lie on a straight line. Thus the least squares method to calculate intercept and slope of this straight line, i.e. A_λ and B_λ, can be applied. These parameters are then used to obtain LD corrected radiance value for the selected pixels, i.e. $A_\lambda + B_\lambda$.

To identify pixels with the same atmospheric coverage, a statistical method has been applied. We describe it giving an example (Fig. 1). Suppose we have different intervals of $\cos\theta$, with every interval containing only 30 points: 10 with the radiance value X, 15 with a different radiance value Y and 5 with another radiance value Z. Supposing that, for every interval of $\cos\theta$, the same radiance value corresponds to the same atmospheric coverage, if our hypothesis are right the data will be disposed on 3 different straight lines. This is exactly what we observe, so it is possible to correct for LD. In the real case (Fig. 2), in every interval of cosine of emission angle, we do not have tens of points, but thousands of points: however, the correction process is the same.

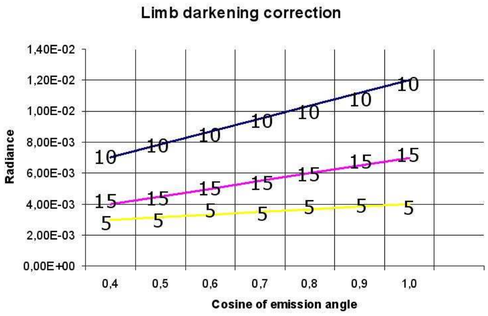

Fig. 1. Limb darkening hypothetical case. It is supposed that only 30 points exist in every interval of cosine of emergence angle.

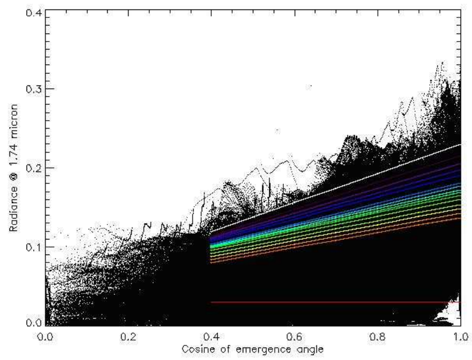

Fig. 2. Limb darkening real case: scatter plot of radiance at 1.74μm as function of cosine of emergence angle. The straight lines are the linear fits used for LD correction. Radiances are in $W/m^2/sr/\mu m$.

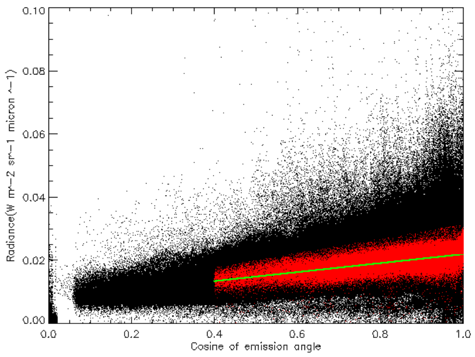

Fig. 3. Scatterplot of radiance at $1.03\mu m$ as function of cosine of emergence angle. Red points are relative to a same interval of radiance at $1.74\mu m$ and surface altitude. These pixels behave in a linear fashion: the green straight line is the best linear fit.

3.2. Limb darkening correction at 1.03 μm

In the case emission comes from surface, A_λ and B_λ depend not only on atmospheric coverage, but also on surface temperature and surface emissivity. The radiance at 1.74 μm (already corrected for LD) can be identified as diagnostic of atmospheric coverage (because 1.74 μm is the atmospheric window with the highest signal-to-noise ratio) and altitude as diagnostic of surface temperature (because the two quantities are inversely proportional, as shown by Avdueskiy et al. 1976). Only surface emissivity remains unknown. Thus pixels having similar 1.74 μm radiance and similar altitude (topography is furnished by Magellan mission data) can be selected: if our hypothesis are right, the radiance from these pixels will be placed on a straight line and a little spread, due to different surface emissivity, will be observed. This is exactly what is observed (Fig. 3). Therefore, for every interval of 1.74 μm radiance and altitude, it is possible to obtain A_λ and B_λ values and correct for LD.

4. Results

Eddington equation can be written in this way: $I_\lambda = I_0(\alpha_\lambda + \beta_\lambda \cos\theta)$, where $I_0 = A_\lambda + B_\lambda$. Carlson et al. (1993) calculated α_λ and β_λ at 1.74 μm and their values are generally used to correct for LD at all wavelengths. On the contrary, we found out that α_λ and β_λ are not constant, depending on the altitude where the emission has been originated. In particular, α_λ increases and β_λ decreases with altitude (Table 1). At 1.74 μm, the values of α_λ and β_λ computed in this work agree with those retrieved by Carlson and colleagues, but, according to our results, these values should not be used to correct for LD at all wavelengths. Using those values will, however, not result in a very large difference in terms of corrected radiance, since the maximum disagreement found is 13%.

Table 1. α_λ and β_λ parameters retrieved in this work and in Carlson et al. (1993).

Wavelength	α_λ	β_λ
Carlson @ $1.74\mu m$	0.316	0.685
$1.03\mu m$ (surface)	0.20 ± 0.02	0.80 ± 0.02
$1.31\mu m$ (0-30 km)	0.23 ± 0.04	0.77 ± 0.04
$1.74\mu m$ (15-35 km)	0.28 ± 0.05	0.72 ± 0.02
$2.30\mu m$ (25-40 km)	0.34 ± 0.03	0.66 ± 0.03
$3.71\mu m$ (60-70 km)	0.40 ± 0.03	0.60 ± 0.03

A physical explanation of the values of α_λ and β_λ retrieved can be given introducing the "attenuation ratio" (AR). We define it as the complement to 1 of ratio between observed radiance at $\cos\theta = 0.4$ and observed radiance from nadir:

$$AR_\lambda = 1 - \frac{I(\cos\theta = 0.4)}{I(\cos\theta = 1)} = 1 - \frac{\alpha_\lambda + 0.4 \cdot \beta_\lambda}{\alpha_\lambda + \beta_\lambda} \quad (2)$$

This number depends on wavelength and is strictly linked to the energy loss of radiation: the more attenuated the radiation, the larger the AR value. It is expected that AR is largest at wavelengths characterised by emission coming from the lowest atmospheric layers: this is what has been obtained by us, as shown in Table 2, explaining the monotone trends of α_λ and β_λ parameters.

It is important to remember that Newman (1975) retrieved parameters of LD curve in the

Table 2. Attenuation Ratio as function of height of starting emission. It can be easily seen that, higher this last, lower the attenuation. This can be due to the lower atmospheric thickness crossed by radiation.

Wavelength	Altitude	Attenuation Ratio
1.03μm	0 km	0.48
1.31μm	0-30 km	0.46
1.74μm	15-35 km	0.43
2.30μm	25-40 km	0.40
3.71μm	60-70 km	0.36

wavelength range 8-14 μm, characterised by emission originating between 65-75 km, finding α_λ=0.54 and β_λ=0.46. These parameters seem to follow the monotone trend with the height where emission is originated found in our work: in this case AR = 0.32, smaller than AR at 3.71 μm, where emission comes from a slightly lower height.
Finally, our predictions at 3.71 μm agree very well with NIMS observations performed by Grinspoon et al. (1993) at the same wavelength. Comparison is in Table 3.

Table 3. Comparison between radiances (normalised respect to their maximum value) measured by Grinspoon et al (1993) (Gr.) at 3.71 micron and our predictions at the same wavelength.

$cos\theta$	I(Gr.)	Err	I(this work)	Err
0.5	0.62	0.02	0.70	0.06
0.6	0.71	0.03	0.76	0.06
0.7	0.81	0.04	0.82	0.07
0.8	0.91	0.03	0.88	0.07
0.9	0.96	0.03	0.94	0.08
1.0	1.00	0.00	1.00	0.00

5. Conclusions

LD effect on Venus nightside data has been studied and corrected. For this purpose, Eddington approximation, which states the linear behaviour of I with $\cos\theta$ has been retained valid. Indeed, parameters of this linear relation have been calculated at five different wavelengths (1.03 μm, 1.31 μm, 1.74 μm, 2.30 μm, 3.71 μm), characterised by emission coming from different altitude ranges (respectively from surface, 0-25 km, 15-35 km, 25-40 km, 60-70 km). It has been found that these parameters are related to the height where emission is originated. This can be explained introducing the "attenuation ratio", a number linked to the attenuation suffered by radiation. It can be seen that the higher the altitude of starting emission, the lower the attenuation, as expected. Results obtained in Newman (1975) agree with the behaviour here found. In addition, our results at 1.74 μm agree with those retrieved by Carlson et al. (1993) at the same wavelength. The use of these to correct for LD also at other NIR wavelengths, as it is common custom, gives corrected radiances similar to those obtained applying the parameters found in this work, with discrepancies never larger than 13%. Finally, our predictions at 3.71 μm agree with the NIMS observations of Grinspoon et al. (1993) at the same wavelength.

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