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DETECTING THE TERRESTRIAL VEGETATION WHILE OBSERVING EARTH AS A SINGLE DOT

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Abstract. Spectroscopic observations of the Earthshine allowed us to make a relative measurement of the integrated Earth reflectance spectrum in which the terrestrial vegetation signature around $\lambda = 700$ nm has been detected. Therefore we conclude that the terrestrial vegetation, and thus terrestrial life, can be detected remotely when the Earth is seen as a single dot. We also conclude that vegetation can be detected on an extrasolar Earth-like planet, if a spectral resolution around 50 is available.

1 Introduction

When future space missions like ESA Darwin (Léger *et al.* 1996) or NASA TPF (Angel & Woolf 1997; Beichman *et al.* 1999) will deliver their first low resolution spectrum of an Earth-like extrasolar planet, it is possible that we will look for spectral signatures able to unveil the possible presence of life on this planet.

Spectral biosignatures can be of two kinds. A first type consists of biological activity by-products, such as oxygen and ozone, in association with water vapour, methane and carbon dioxide (Lovelock 1975; Owen 1980; Angel *et al.* 1986). These biogenic molecules present attractive narrow molecular bands. But oxygen is not a universal by-product of biological activity as demonstrated by the existence of anoxygenic photosynthetic bacteria (Blankenship *et al.* 1995).

A second type of biosignature is provided by signs of stellar light transformation into biochemical energy, such as the planet surface colour from vegetation (Labeyrie 1999). This spectral signature is in principle a more universal biomarker than any biogenic gas such as oxygen, since it is a general feature of any photosynthetic activity. Unfortunately, it is often not as sharp as single molecular

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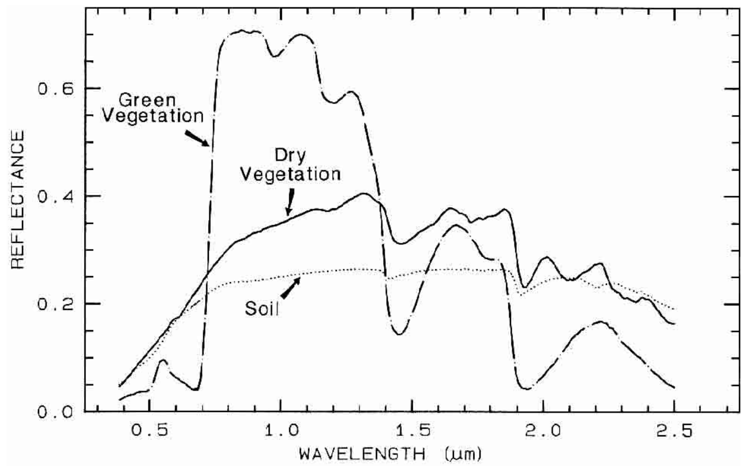

Fig. 1. Reflectance spectra of photosynthetic (green) vegetation, non-photosynthetic (dry) and a soil (from Clark 1999). The so-called vegetation red edge (VRE) is the green vegetation reflectance strong variation from ≈5% at 670 nm to ≈70% at 800 nm.

bands: although it is rather sharp for terrestrial vegetation at ≈700 nm (Clark 1999; Coliolo *et al.* 2000, see Fig. 1), its wavelength structure can vary significantly among bacteria species and plants (Blankenship *et al.* 1995).

Before initiating a search for extrasolar vegetation, it is useful to test if terrestrial vegetation can be detected remotely. This seems possible as long as Earth is observed with a significant spatial resolution (Sagan *et al.* 1993), but is it still the case if Earth is observed as a single dot? A way to observe an *integrated Earth* is to observe the Earthshine with the Moon acting like a remote diffuse reflector illuminated by our planet. We present in Section 2.1 normalized Earth albedo spectra derived from Earthshine, showing several atmospheric signatures. We show in Section 2.2 how the vegetation signature around 700 nm can be extracted.

2 Observations and Results

The Earthshine has been observed in 2001 with a low resolution spectrograph installed on the 80 cm telescope at Observatoire de Haute-Provence.

2.1 Earth Albedo $EA(\lambda)$

It can be shown (Arnold *et al.* 2002) that the normalized Earth albedo is simply given by the ratio

$$EA(\lambda) = \frac{ES(\lambda)}{MS(\lambda)} \tag{2.1}$$

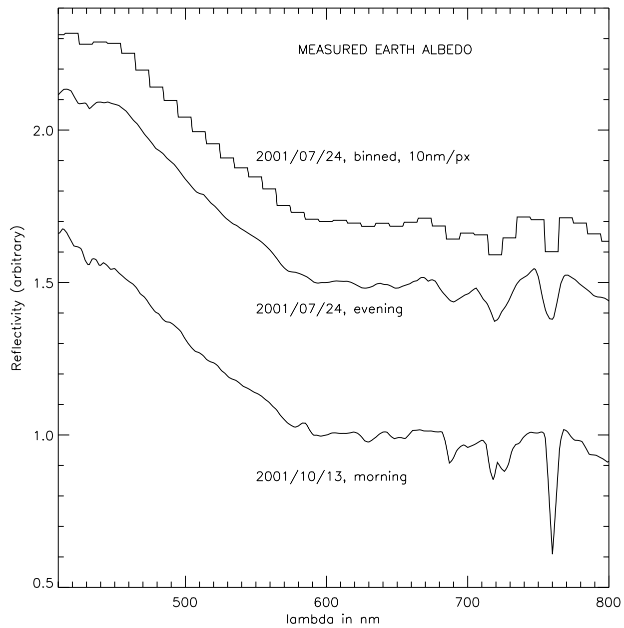

Fig. 2. Examples of measured Earth albedo spectra. Both spectra are normalized to 1 at 600 nm, but the July spectrum is shifted upwards by 0.5 for clarity. The spectral resolution was ≈50 in July, and ≈240 in October. The July spectrum has been binned to 10 nm/px to mimic the low resolution that might be used for the first extrasolar planet spectrum.

where $ES(\lambda)$ and $MS(\lambda)$ are the measured Earthshine and sunlit Moon spectra, respectively. The result is shown in Figure 2. The higher reflectivity in the blue shows that the Earth should be seen as a blue object from space. This is due to the Rayleigh scattering in the atmosphere and not only to the intrinsic blue colour of the ocean (discussed later in Fig. 3). The H_2O bands around 690 and 720 nm, and O_2 narrower band at 760 nm are clearly visible with a resolution of $R \approx 50$. The slope variation occurring at ≈600 nm is partially the signature of the deepest zone of the broad ozone absorption band (Chappuis band).

2.2 *Earth Surface Reflectance SR*(λ)

Although the vegetation is partially responsible for the higher level of the spectrum above $\lambda = 730$ nm in Figure 2, doing a quantitative measurement of the vegetation signal requires to remove the atmospheric absorption bands in this spectral region. Earth surface reflectance $SR(\lambda)$ can be written by the simple scalar definition

$$EA(\lambda) \approx SR(\lambda) \times AT^{\alpha=2}(\lambda) \tag{2.2}$$

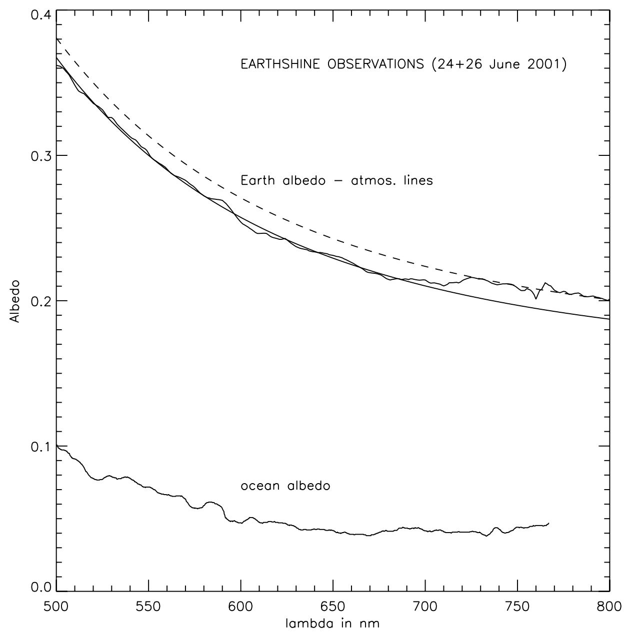

Fig. 3. An example of Rayleigh correction: the graph shows the 24+26 June spectrum $SR(\lambda)$ (above) after atmospheric absorption correction (Eq. (2.2)), but still containing the Rayleigh scattering signature. The spectrum is fitted with a Rayleigh law adjusted over the [500; 670 nm] window. The fit is then translated (dash) and adjusted to the [740; 800 nm] region of $SR(\lambda)$ to show the VRE (here $VRE = 7\%$). $SR(\lambda)$ is normalized to 0.3 at 550 nm (Goode *et al.* 2001) to be compared to the ocean albedo (McLinden *et al.* 1997). The $SR(\lambda)$ higher slope in the blue is the signature of Rayleigh diffusion in Earth's atmosphere rather than simple ocean reflectivity (Arnold *et al.* 2002).

where $AT(\lambda)$ is the mean Earth atmospheric transmittance. The exponent $\alpha = 2$ represents the typical airmass crossed by solar photons before going to the Moon.

The spectrum $AT(\lambda)$ is measured and α is adjusted in order to remove all the atmospheric bands (Arnold *et al.* 2002) as shown in Figure 3. $SR(\lambda)$ does not represent the pure surface reflectance, but includes uncorrected atmospheric scattering. The Figure 3 shows $SR(\lambda)$ fitted with the Rayleigh law $A + B/\lambda^4$ adjusted over the [500; 670 nm] window. The slope towards the blue does not hide the relatively sharp vegetation signature, which appears around 700 nm. $SR(\lambda)$ is then normalized to the Rayleigh fit (Fig. 4).

To quantify the vegetation signature, we define the Vegetation Red Edge (VRE) as

$$VRE = \frac{r_I - r_R}{r_R} \tag{2.3}$$

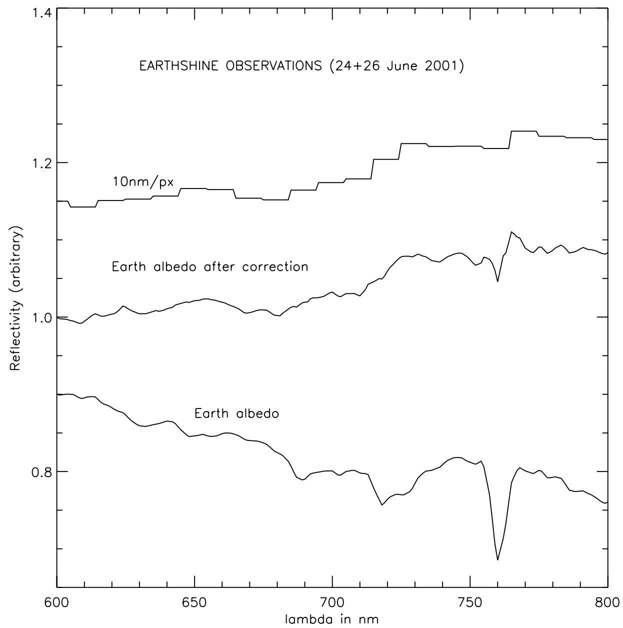

Fig. 4. An example of data reduction sequence: the graph shows the June albedo spectrum $EA(\lambda)$ (bottom). All atmospheric absorption features are then corrected according to equation (2.2) and the spectrum is flattened with a Rayleigh law adjusted in the [500; 670 nm] window (Fig. 3). The result is shown above with 1 and 10 nm/px resolution. The measured red edge around 700 nm is $VRE = 7\%$ (Eq. (2.3)).

where r_R and r_I are the mean reflectances in the [600; 670 nm] and [740; 800 nm] windows in the spectrum after it has been flattened with a Rayleigh law as explained above. Flattened $SR(\lambda)$ spectra are shown in Figure 5.

3 Discussion and Conclusion

We have found a VRE ranging from 4 to 10% with an accuracy estimated to be $\sigma \approx 3\%$ (Arnold *et al.* 2002). These results are in agreement with estimations from models predicting 2 to 10% (Des Marais *et al.* 2001; Schneider 2000a; Schneider 2000b; Arnold *et al.* 2002) and other measurements done in 2001 by Woolf *et al.* (2002).

Although it seems that the Earth's vegetation signature might be visible as a red edge at 700 nm, it is difficult to measure in the Earthshine for two reasons. The first reason is related to its variable amplitude, induced by a variable cloud cover and Earth phase. The second reason is because it is hidden below strong atmospheric bands which need to be removed to access the surface reflectance including the vegetation signature.

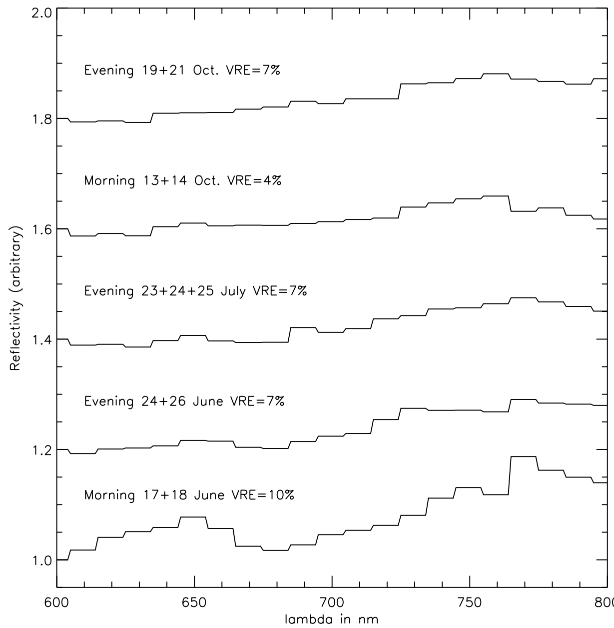

Fig. 5. Collection of $SR(\lambda)$ spectra normalized to 1 at 600 nm, but shifted upwards for clarity by 0.2, 0.4, 0.6 and 0.8, respectively. Note that only the $[600; 670]$ and $[740; 800$ nm$]$ windows are used to estimate the VRE. The spectra are binned to 10 nm/px.

For the Earth, our knowledge of different surface reflectivities (deserts, ocean, ice etc.) help us to assign the VRE of the Earthshine spectrum to terrestrial vegetation. For an exoplanet, a VRE-like index might be as difficult to measure as for the Earth due to variable cloud cover of the planet. Even if an extrasolar planet would give a clear VRE-like spectral signal, its use as a biosignature would raise some questions because: i) for several organisms (such as *Rhodopseudonomas*, Blankenship *et al.* 1995) the “red edge” is not at 700 nm, but at 1100 nm; ii) some rocks, like schists, may have a similar spectral feature. For instance, spectra of Mars show a similar spectral feature at 3.5 μ, which were erroneously interpreted as vegetation due to their similarity with lichen spectra (Sinton 1957).

We nevertheless believe that, associated with the presence of water (and secondarily oxygen) and correlated with seasonal variations, a vegetation-like spectral feature would provide more insight than simply oxygen on the bio-processes possibly taking place on the planet. But since water, and thus clouds and rain, are essential for the growth of vegetation, extrasolar planets with a very low cloud cover and a corresponding high vegetation index are unlikely, more especially if the planet is seen pole-on, with a bright white polar cover. On the other hand, an extrasolar planet vegetation surface could be larger than on Earth (like during periods in the paleozoic and mesozoic eras on Earth for example).

One must also note that the measurement of an extrasolar planet VRE will not suffer from the intrinsic difficulty of the same measurement for the Earth through the Earthshine spectrum: the extrasolar planet albedo will simply be given by the ratio of spectra $planet/mother\ star$. But a model of the exoplanet atmosphere is necessary to be able to remove the absorption bands that may partially hide the vegetation. Although the probability is weak, the planet may occult a background star, thus providing us a direct measurement of the planet atmosphere absorption.

The detection of a VRE index between 0 and 10% requires a photometric precision better than 3%. Exposure time to achieve this precision with Darwin/TPF on an Earth-like planet at 10 pc with a spectral resolution of 25 is of the order of 100 h based on recent simulations (Riaud *et al.* 2002).

Finally, the Earth albedo spectral variations study is of interest for global Earth observation. It might provide data on climate change, as broad-band measurements recently showed (Goode *et al.* 2001). We also think that the spectrum of Earthshine might be used for example to monitor the global ozone (with the Chappuis or Huggins bands).

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