Detectability of Planetary Characteristics from Spatially and Spectrally-Resolved Models of Terrestrial Planets: Mars and Earth

G. Tinetti (JPL/USC), V. S. Meadows (JPL/Caltech), D. Crisp (JPL), T. Velusamy (JPL), J. F. Kasting (PSU), A. Segura (PSU), K. Krelove (ASU), W. Fong (Caltech) & H. Snively (UCSC)

Abstract

The principal goal of the NASA Terrestrial Planet Finder (TPF) mission is to detect and characterize extrasolar terrestrial planets. However, the first generation of instruments for studying extrasolar planets are expected to provide only disk-averaged spectra with modest spectral resolution and signal to noise. As a part of the NASA Astrobiology Institute's Virtual Planetary Laboratory (VPL, V. Meadows, PI) we are exploring what can be learned about a planet's surface and atmospheric properties from disk-averaged spectra at a number of spectral resolutions at visible and IR wavelengths. We are using a spectrum resolving (line-by-line) atmospheric/surface radiative transfer model (SMART, D. Crisp) and atmospheric and surface data for Earth, Mars, Venus and Titan to generate a database of spatially resolved synthetic spectra for a range of illumination conditions (phase angles) and viewing geometries. These results are then processed with a model that resamples the spatially resolved spectra to create a synthetic, disk-averaged view of the planet from a specific viewing geometry. To validate these methods, we have compared observational data with our synthetic spectra of Mars and Earth. We will present a complete study of Mars, and the first results for Earth, including disk-averaged synthetic spectra, images and the spectral variability at visible and mid-IR wavelengths as a function of viewing angle. We have also simulated an increasingly frozen Mars, and have studied the detectability of CO_2 ice in the disk averaged spectrum, using a TPF instrument simulator. We have determined that surface CO_2 ice can be spectrally identified in a TPF mid-IR spectrum of a disk-averaged Mars, even at low resolution, if the ice cap extends down to at least 50 degrees latitude from the pole.

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Introduction

The principal goal of the NASA Terrestrial Planet Finder (TPF) mission concept is to detect and characterize extrasolar terrestrial planets. TPF is expected to survey nearby stars and directly detect planetary systems that include terrestrial-sized planets in their habitable zones. These measurements may also determine whether these planets harbor life.

Characterization of terrestrial planets can best be achieved via remote sensing spectroscopy. Given the spectrum of a planet, it is possible to derive information about the chemical composition, thermodynamics and kinetics of its atmosphere, the composition of its surface, and then potentially to infer about the underlying dynamics on the planet.

The NAI Virtual Planetary Laboratory (VPL, a.k.a. JPLII, Dr. Victoria Meadows, P. I.), seeks to understand the extent to which the environments of extrasolar terrestrial planets can be characterized from disk-averaged visible and infrared spectra.

Approach

As part of understanding how to characterize extrasolar terrestrial planets, we are exploring what can be learned about a planet's surface and atmospheric properties from disk-averaged spectra at a number of spectral resolutions.

To do this, we have derived an architecture for a planet simulation model that takes into account "tiling" or pixelization of the sphere and the way in which the tiles map back to surface types. After having considered different mapping geometries, we have decided to use Healpix pixelisation. We then have used a radiative transfer model (SMART) and atmospheric and surface data for Mars to generate synthetic spectra at the Healpix resolution for a range of illumination conditions (phase angles) and viewing geometries.

Finally, we have created a program, which takes user specifications of spatial resolution and selects the appropriate radiative transfer spectra generated by SMART for each pixel of the simulation (taking into account local albedo, viewing angle and sun-position) to produce the final synthetic view, which can then be disk-averaged. We have repeated this procedure for several days, and compared the results with experimental data.

SMART

The Spectral Mapping Atmospheric Radiative Transfer (SMART) model [(Meadows and Crisp, 1996), (Crisp 1997)], is the principal model that has been used to generate the high-resolution synthetic spectra of planetary atmospheres. SMART is a multi-stream, multi-level, spectrum- resolving (line-by-line) multiple-scattering algorithm. Using a high-resolution spectral grid it completely resolves the wavelength dependence of all atmospheric constituents, including absorbing gases (infrared absorption bands, UV predissociation bands, and electronic bands) and airborne particles (clouds, aerosols) at all levels of the atmosphere, as well as the wavelength-dependent albedo of the planet's surface, and the spectrum of the incident stellar source.

In summary, SMART:

- simulates both solar/stellar and thermal sources,
- includes a rigorous (monochromatic) treatment of multiple scattering by gases, clouds, and aerosols, at both solar and thermal wavelengths,
- can use all available constraints on the wavelength-dependent optical properties of gases, airborne particles, and a reflecting surface,
- can incorporate all available constraints on the vertical distributions of temperatures, trace gases, and airborne particles (clouds, aerosols),
- provides a detailed, angle-dependent description of the radiation field, facilitating the derivation of disk-integrated results from any viewing angle,
- evaluates spectrally-integrated fluxes throughout the atmosphere, facilitating the derivation of solar heating rates, thermal cooling rates and photochemical reaction rates.

[Ref1] V. S. Meadows, D. Crisp, *Ground-based near-infrared observations of the Venus nightside: The thermal structure and water abundance near the surface*, (Journal of Geophysical Research, vol. 101, 4595-4622)

[Ref2] Crisp D., ***Absorption of sunlight by water vapor in cloudy conditions: A partial explanation for the cloud absorption anomaly.*** , Geophys. Res. Lett., 24, 571-574, 1997.

Healpix

Healpix (Hierarchical Equal Area and iso-Latitude Pixelisation) is a curvilinear partition of the sphere into exactly equal area quadrilaterals of varying shape. The base resolution comprises twelve pixels in three rings around the poles and equator. Healpix was originally designed for the COBE mission by Krzysztof M. Górski, Eric Hivon, Benjamin D. Wandelt, 1998).

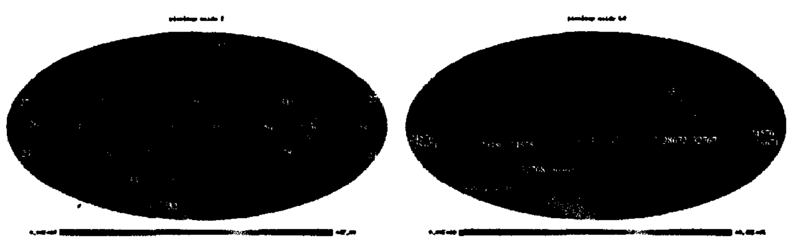
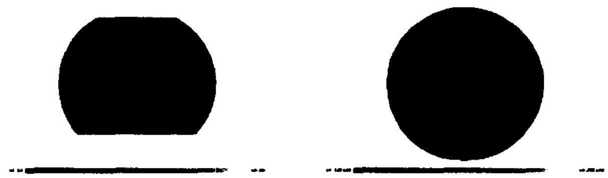
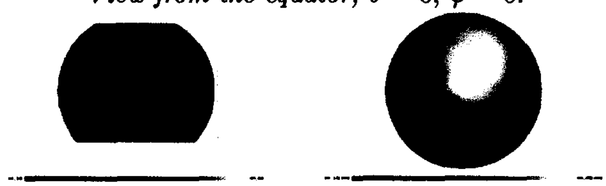


Fig. *1 In these figures we show two different resolutions corresponding to* $N_{pix}^{tot} = 48$ *and* $N_{pix}^{tot} = 49152$.

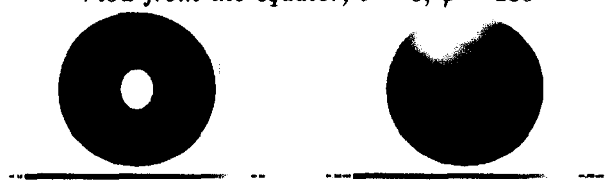
Viewing geometries



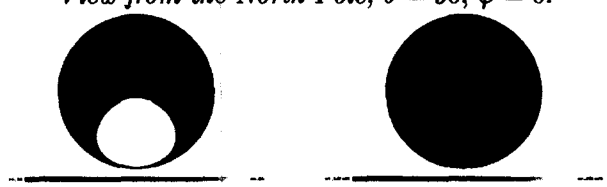
View from the equator, $\theta = 0$, $\varphi = 0$.



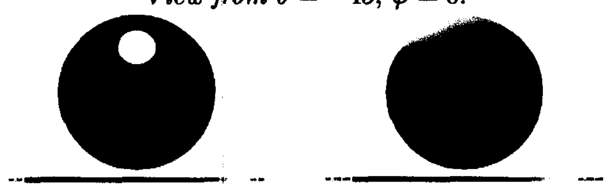
View from the equator, $\theta = 0$, $\varphi = 180$



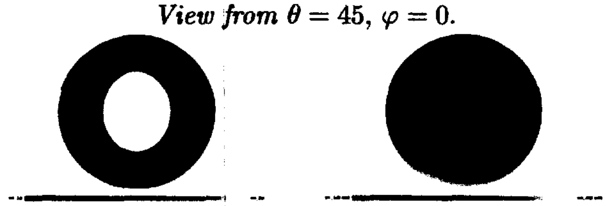
View from the North Pole, $\theta = 90$, $\varphi = 0$.



View from $\theta = -45$, $\varphi = 0$.



View from $\theta = 45$, $\varphi = 0$.



View from the South Pole, $\theta = -90$, $\varphi = 0$.

Fig. 2 *These figures show a simulation of the temperature field (right, 140-280 K) and solar albedo (left, 0.1-0.6), for a day on Mars close to solstice, $L_s = 104.58°$ and from different viewing angles. The polar caps extend for $\sim 15°$ in the northern hemisphere, and $\sim 40°$ in the southern hemisphere.*

Mars Disk-averaged synthetic spectra

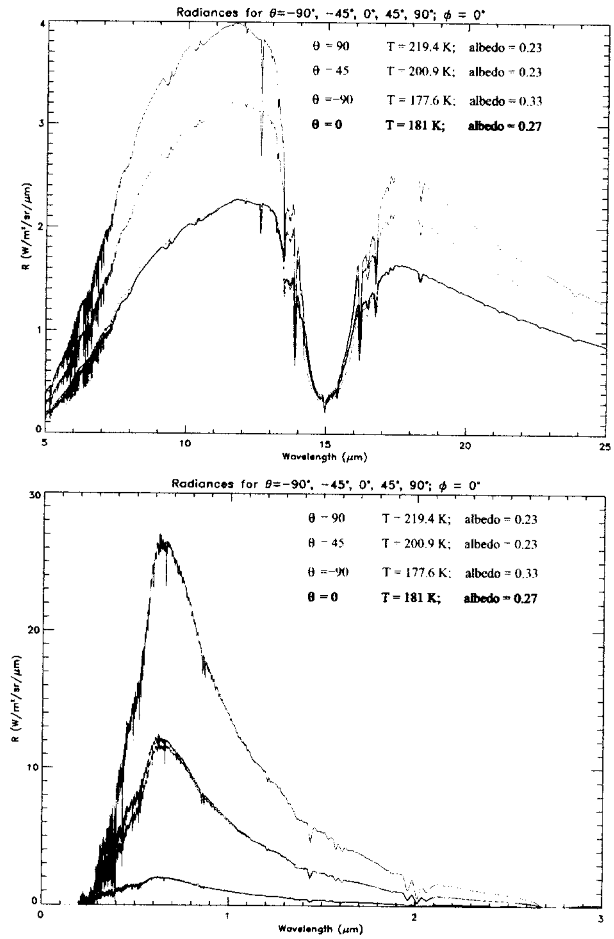


***Fig. 3** Variability of disk-averaged synthetic spectra. Synthetic spectra for sub-viewer points with different latitudes (longitude = 0°): $\theta = 0°, 45°, 90°, -45°, -90°$, and the corresponding disk-averaged temperature and solar albedo.*

The polar caps extend ∼ 15° to the South in the northern hemisphere, and ∼ 40° to the North in the southern hemisphere.

Frozen Mars

We have simulated to cover the surface of the planet with an increasing amount of ice in order to study the detectability of the polar-caps on a planet when only when we have a disk-averaged spectrum. Polar-cap spectra have very strong features, but to start detecting them we have at least to extend the ice coverage to $\sim 50°$.

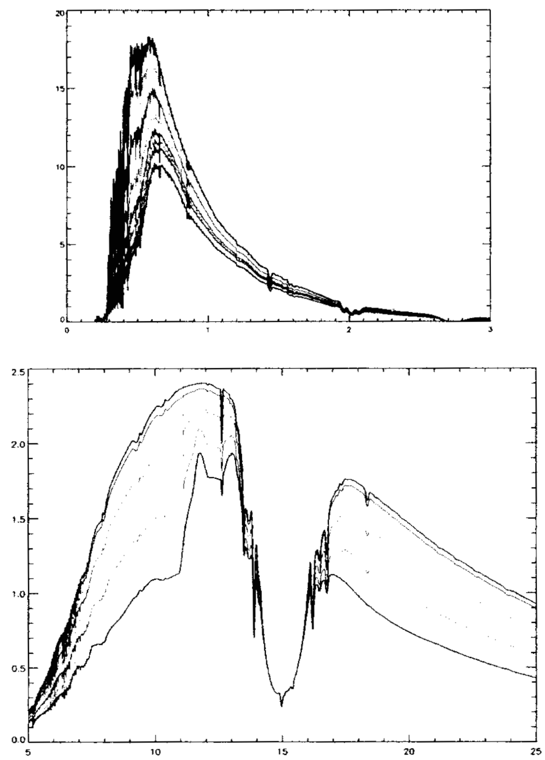


***Fig.** 4 Disk-averaged spectra of the southern polar-cap area (supposed extending for* 0° *(black),* 20° *(violet),* 40° *(light-blue),* 50° *(green),* 60° *(yellow),* 70° *(red),* 80° *(grey),* 90° *(black) For increasing extension of the polar-cap area the CO_2 ice features are more and more detectable. Abscissas: wavelength in μm, ordinates: radiation in $W/m^2/sr/\mu$.*

Simulation of a TPF detection of Mars Polar-cap

Our synthetic disk-averaged spectra were run through a TPF observation system simulator for different spectral resolutions. The TPF book design has been assumed for these calculations (four 4m teselcopes on a 75m baseline), and the planet was placed around a G star that is 10pc distant. TPF will provide only disk-averaged spectra with possible spectral resolutions of ~75 (visible) and ~25 (MIR), depending on final architecture. The top spectrum in each set is at high-resolution, and the middle and lower panels show R~100 (at 10 days integration) and R~20 (at 2 days integration) respectively. 1-σ error bars are shown in red. Mars at 10pc shows poor S/N, even at 2 days integration (R~20).

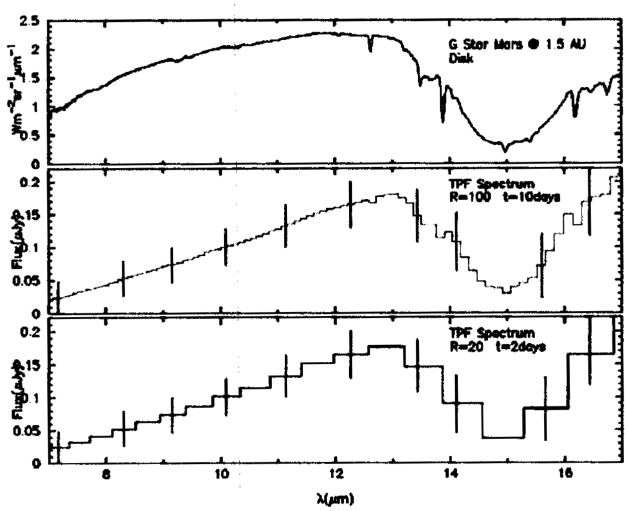


***Fig. 5** Simulation of TPF detection of a disk averaged spectrum.*

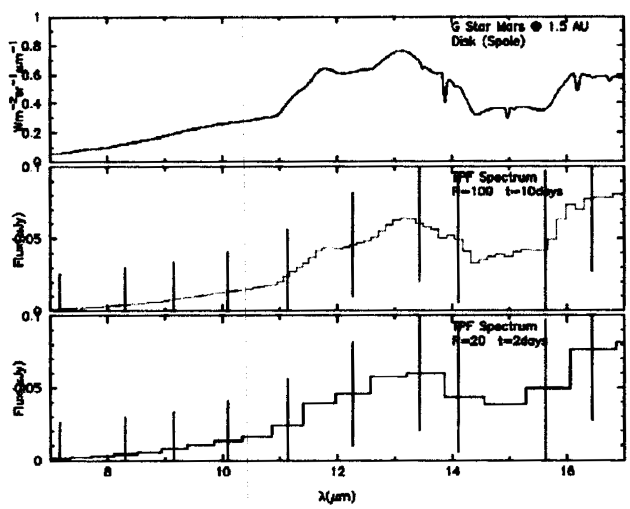


***Fig. 6** Simulation of TPF detection of a South polar-cap spectrum.*

Simulation of a TPF detection of a Earth-like planet orbiting G, F, K stars

Here we show similar results for detectability and characterization of an Earth-like planet with the modern oxygen abundance, around stars of different spectral type (F,G,K). The high resolution synthetic spectra were also generated with SMART, based on atmospheres generated by a coupled-climate-chemistry model developed by Kasting, Segura and Krelove and described in detail in "Ozone Concentrations and Ultraviolet Fluxes on Earth-like Planets Around Other Stars" by A. Segura, K. Krelove, J. F. Kasting, D. Sommerlatt, V. S. Meadows, D. Crisp, M. Cohen and E. Mlawer, submitted to *Astrobiology*, 2003.

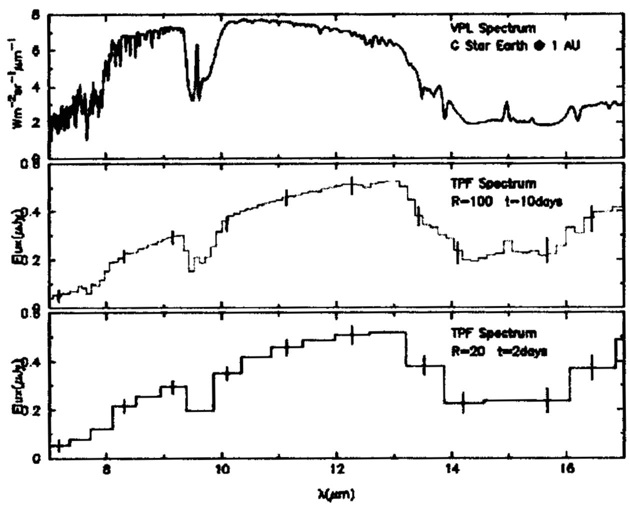


***Fig. 7** Simulation of TPF detection of a Earth-like planet orbiting around a G star.*

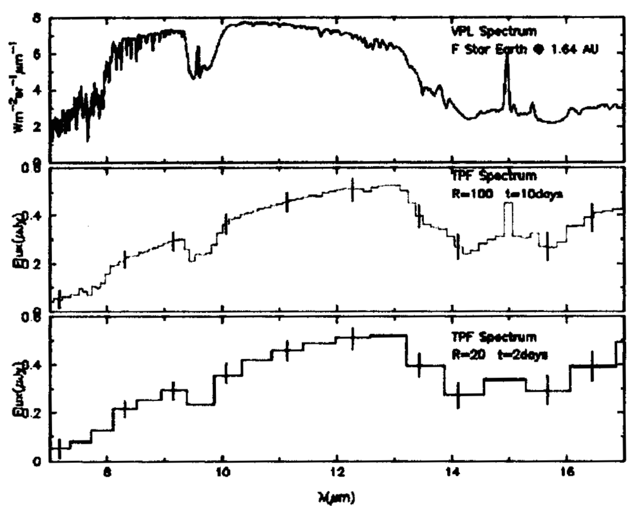


***Fig. 8** Simulation of TPF detection of a Earth-like planet orbiting around a F star.*

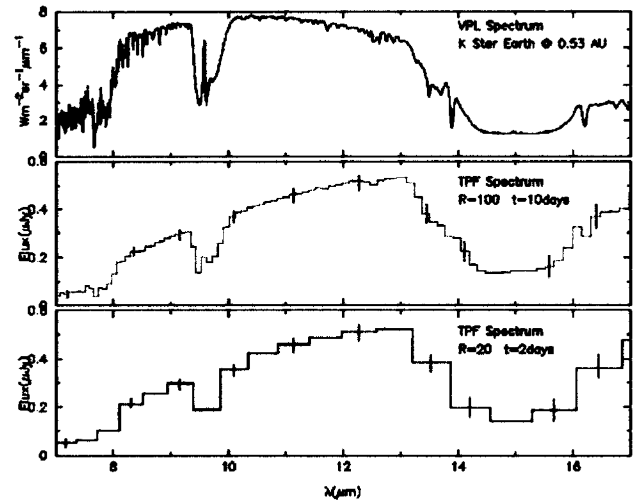


Fig. 9 Simulation of TPF detection of a Earth-like planet orbiting around a K star.

Conclusions

- Disk-averaging reduces the detectability of most of the local properties, and even a prominent ice-cap cannot be detected in the MIR, unless it covers down to 50-60 degrees from the pole (Fig. 4)
- However, if a significant fraction of the planet is covered with CO2 ice ($\geq$ 70 degrees from the pole), with sufficient S/N it is still possible to identify the CO_2 ice feature, even at a R $\sim$ 20 (Fig 6.)
- Although it is possible to discriminate between Mars and Earth at R$\sim$20, at higher resolution we are much better able to characterize the temperatures of the surface and atmosphere via features such as the CO_2 15μm band.
- The temperature inversion in the Earth's atmosphere, which produces the emission peak at the center of the CO_2 15μm band, can be used as a secondary (confirmation) indicator of the presence of a high-altitude absorber such as ozone.
- The detectability of atmospheric features such as CO_2, O_3 and CH_4 on an Earth-like planet changes as a function of the spectral type of the parent star (Segura et al., 2003)