Characterizing Earth in the Mid-Infrared from an Observer's Perspective

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How accurately can we characterize Earth form its mid-infrared (MIR) emission?

Disk-Integrated Earth Spectra

We study a set of **real disk-integrated** MIR thermal emission **spectra of Earth** [1]. We consider **monthly** flux averages for January (Jan) and July (Jul) as well as three **viewing angles**: North Pole (NP), South Pole (SP), and Equatorial Combined (EqC) (Fig. 1). All spectra exhibit a gap between 4.6 and 6.2 micron due to several dead AIRS instrument channels [2]. We use additional data from AIRS to derive **ground truths** of atmosphere and planet parameters, which we compare our retrieval results to.

To simulate observations of Earth with the Large Interferometer For Exoplanets (LIFE), we assume Earth to orbit a **G2V star** located **10 pc** from the observer and use **LIFEsim** [3] to simulate the astrophysical noise expected for LIFE observations of such a planet. We simulate spectra for different combinations of **noise** (S/N = 10, 20) and **spectral resolution** (R = 50, 100).

Retrievals on such Earth remote sensing data will help us **understand how exoplanet observations can be safely analyzed**. By treating Earth as an exoplanet, we study how our **characterization depends on the observed viewing angle or season**. We also investigate if **retrievals that use simple 1D forward models** can correctly characterize atmospheres. Finally, we study how **patchy clouds** can affect our characterization.

Figure 1: Disk-integrated R = 50 MIR spectra of different Earth views and months. The shaded areas indicate the S/N = 10 and S/N = 20 LIFEsim noise levels.

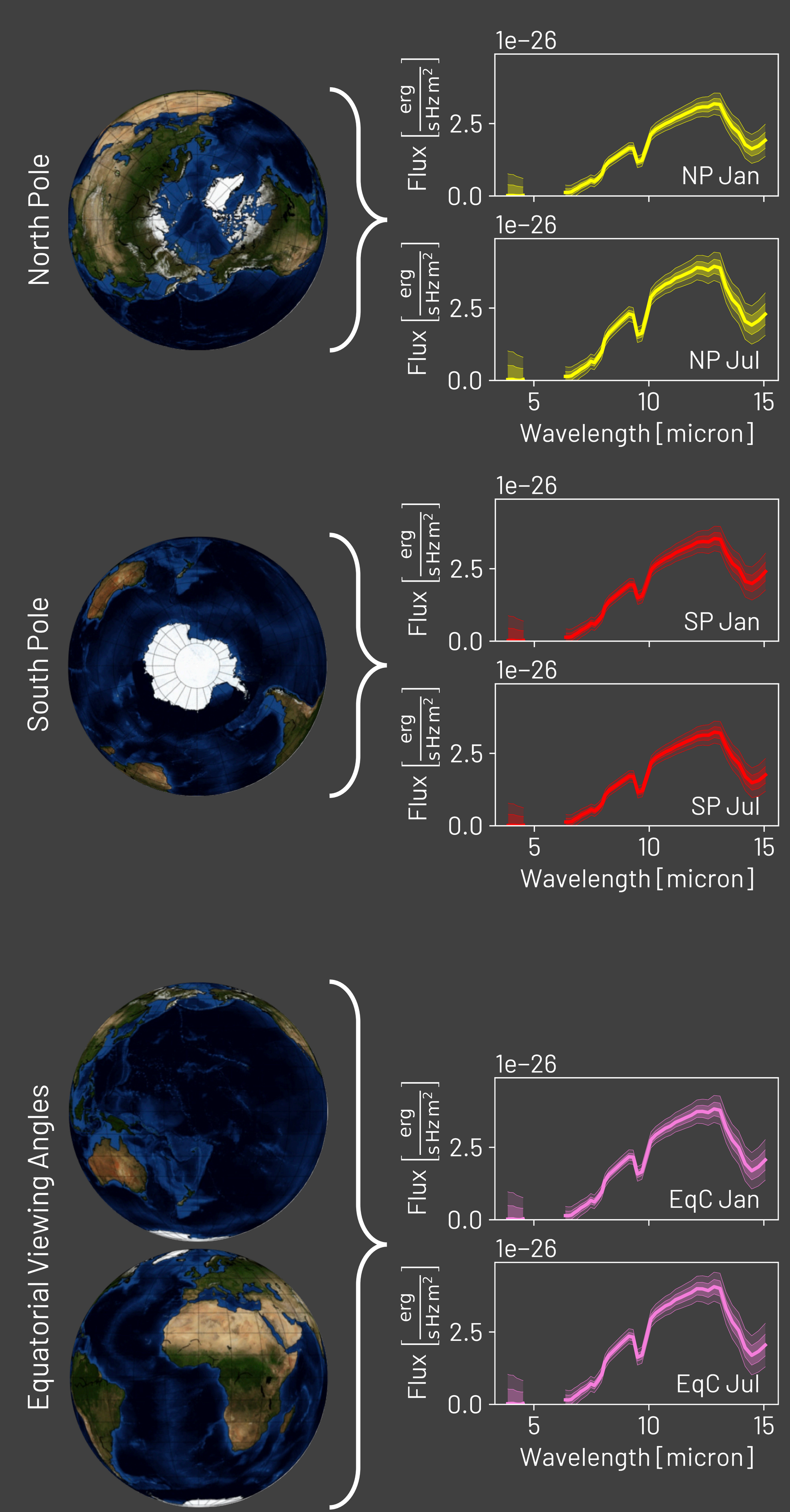
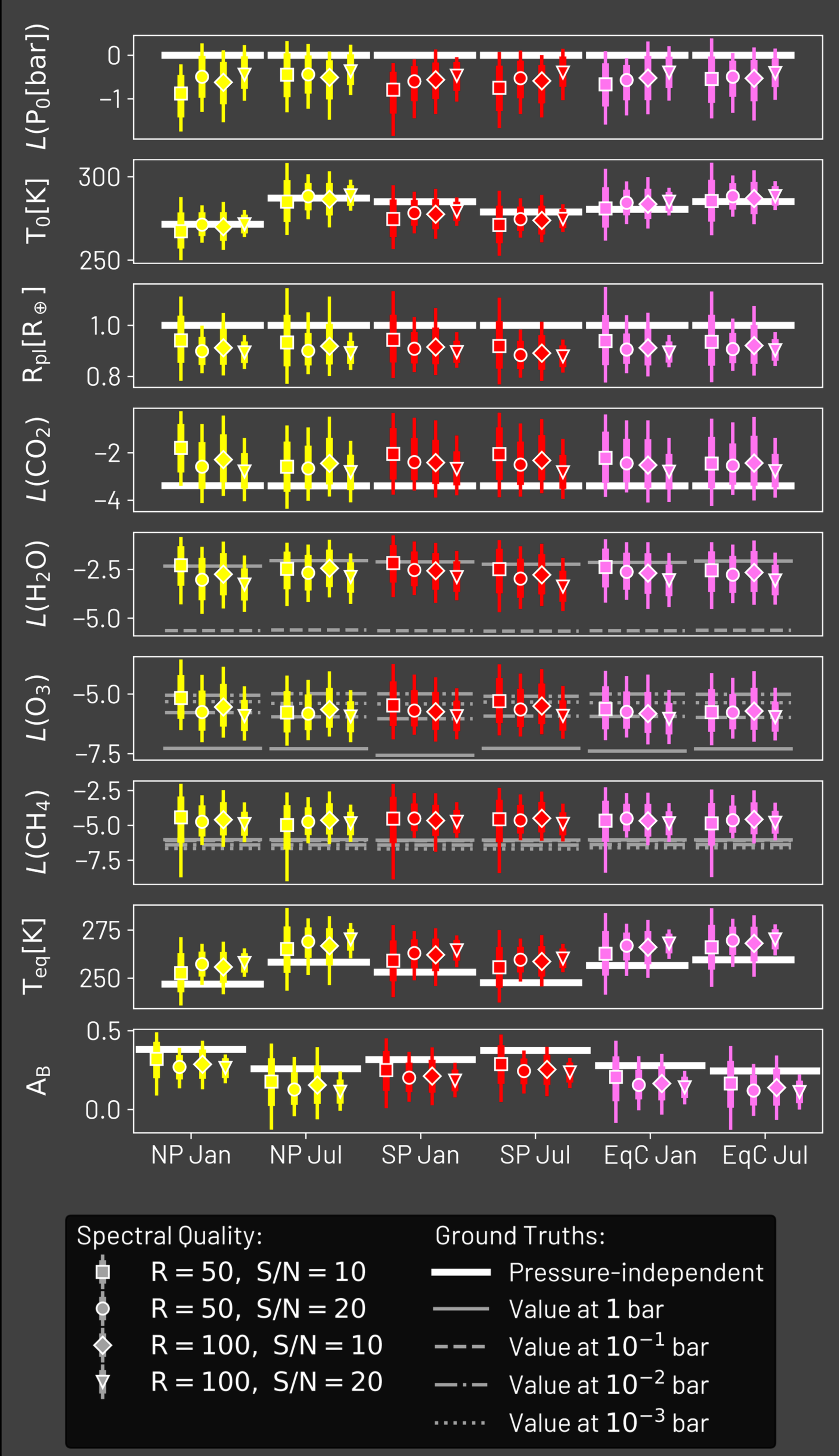


Figure 3: Posteriors for different views, months, R, and LIFEsim S/N. Spectral R and S/N are indicated by the marker shape, the color marks the view. Colored lines show posterior percentiles (thick: 16%–84%; thin: 2%–98%). Thick white lines are pressure independent ground truths. Pressure dependent ground truths are shown as gray lines (solid: 1 bar; dashed: 10^{-1} bar; dashed-dotted: 10^{-2} bar; dotted: 10^{-3} bar). L(•) abbreviates log10 (•).



Retrieval Results and Conclusions

Our retrievals would characterize Earth as a **temperate habitable planet** with detectable levels of **CO_2, H_2O, O_3, and CH_4** (Fig. 3). Thus the viewing angle and the season **only have a minor impact on the detectability of molecules**. For the surface temperature T_0, equilibrium temperature T_{eq}, and Bond albedo A_B the **seasonal variations of 33% for the NP view could be detectable** for high R and S/N. Additionally, we find that the small **seasonal variations in biosignature gases on Earth are not detectable** for all R and S/N considered.

However, our results for P_0, R_{pl}, T_{eq}, A_B, and the abundances are **biased relative to the ground truths**. The biases are most likely evoked by our simple **cloude-free 1D Earth model which we fit to time- and disk-integrated 3D Earth spectra**. Our 1D model cannot describe Earth's true atmospheric state and its MIR spectrum. Therefore, the **parameter values that best describe an observation do not necessarily provide good** estimates for the ground truths. Thus, retrievals on observed exoplanet spectra **will likely yield biased estimates**.

Despite these issues, Earth would present itself as a planet where life could thrive, with **detectable levels of bioindicators, a temperate climate, and a surface pressure that allows for liquid surface water.**

Background – Retrievals

An atmospheric retrieval searches the **best fit of a model for an exoplanet's spectrum to an observed spectrum**. Further, it yields Bayesian estimates and uncertainties for the model parameters (Fig. 2). These model parameters describe the planet's bulk and atmospheric properties (e.g. the exoplanet radius, pressure-temperature profile, surface conditions, and abundances of gases in the atmosphere). Our retrieval framework [4,5,6] relies on **two subroutines**:

1. **A radiative transfer routine** (petitRADTRANS [7]), to calculate the spectrum corresponding to the 1D atmosphere described by the model parameter values.
2. **A Bayesian parameter estimation code** (MultiNest [8] via pyMultiNest [9], which uses Nested Sampling [10]), to find the set of parameters values (and uncertainties) best fitting the observed spectrum.

Figure 2: By running atmospheric retrievals on observed exoplanet spectra we can infer planet and atmosphere properties.

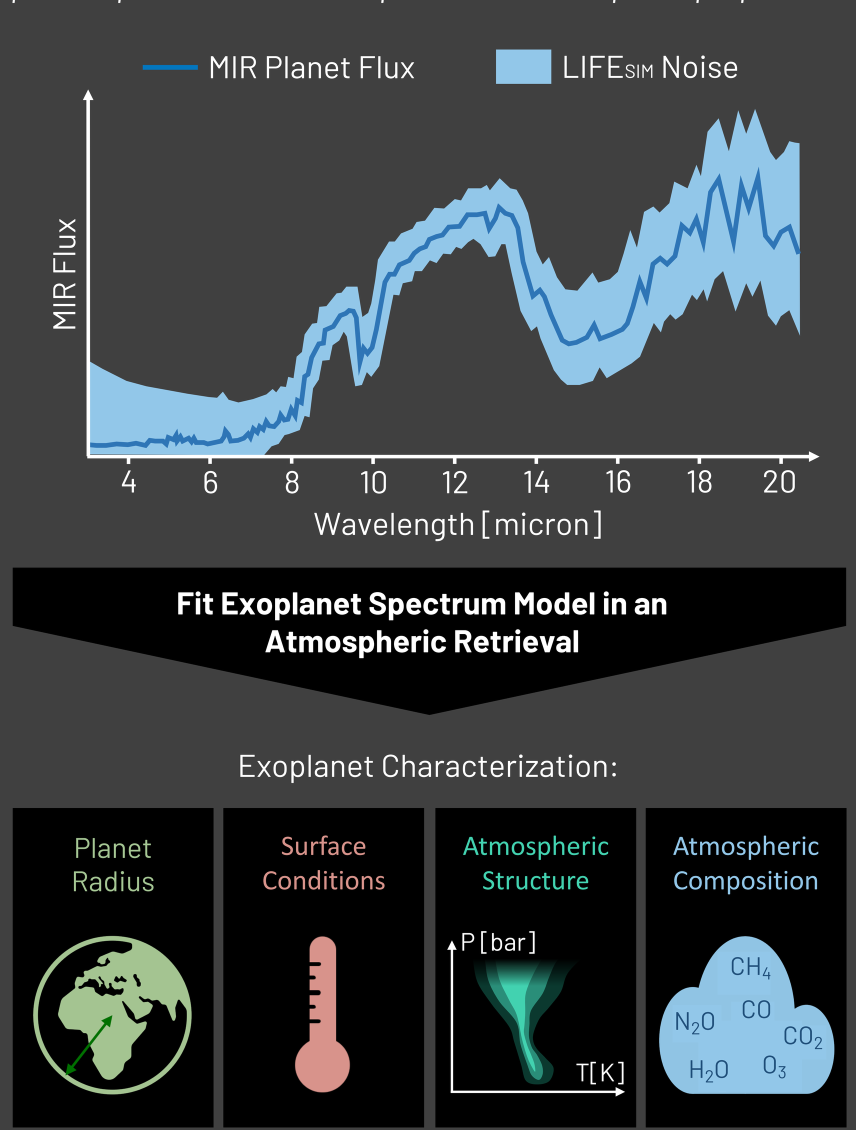
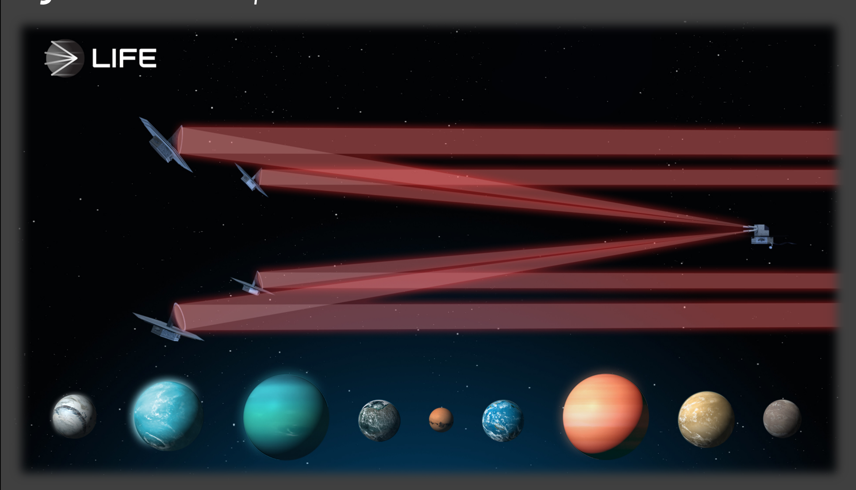


Figure 2: Artist impression of the LIFE interferometer.



Background – LIFE

Our goal is to characterize the atmospheres of terrestrial exoplanets, assess their habitability, and search for signs of life. **Large space-based direct-imaging missions are required** to achieve this. NASA's Habitable Worlds Observatory mission concept aims to measure the stellar light reflected by the exoplanet in the visible (VIS) and near-infrared (NIR) wavelength range.

The **LIFE interferometer** [11] concept aims to measure the **MIR thermal emission** of a large sample of terrestrial exoplanets. Such measurements can only be obtained with a **space-based nulling interferometer** (Fig. 4) The LIFE initiative's aim is to work toward the launch of such an instrument.

LIFE will probe the MIR wavelength range instead of the NIR/VIS range because **more atmospheric gases have strong absorption features in the MIR**. This allows for a better assessment of the atmospheric structure and composition [12, 13]. Further, emission spectra can provide stronger constraints on the planet radius. Finally, the MIR provides access to many biosignatures (detectable spectral features produced by biotic processes). An example of a biosignature is the simultaneous presence of large amounts of O_3 and CH_4 [14], which are both detectable in the MIR.

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