

Can LUVex detect methane on an Archean Earth-like planet during its search for candidate exoEarths?

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1 Introduction

The LUVOIR final report argues for two main phases of telescope operations in its search for life on exoplanets:

1. A planet detection phase. Detect planets with photometry at 550 nm and do a single spectroscopy bandpass of each detected planet searching for the 0.94 μm water vapor feature. Detected planets with water vapor establish a list of habitable exoEarth candidates.
2. A planet characterization phase. Further observations are made to search for habitability and biosignatures on the exoEarth candidates identified in step (1).

During step (2), we must slowly piece together a spectrum, and our knowledge of the planet, in a sequence of bandpasses. The coronagraph on LUVex will likely not be capable of doing spectroscopy bandpasses ($B = \frac{\Delta\lambda_b}{\lambda}$) that span an entire channel (e.g. the visible channel spans 0.5 to 1.0 μm). Instead, we currently expect bandpasses to be on the order of $\sim 15\%$ to $\sim 30\%$.

This limitation of LUVex brings up the following question: What is the most optimal sequence of bandpasses to most efficiently identify an inhabited or uninhabited planet? Efficiency is critical, because telescope observation time is limited and we want to allocate time in a way that allows us to learn the

most about the likelihood of life on detected exoEarth candidates.

Shawn Domagal-Goldman, Giada Arney and others on the LUVex team are working on an optimal sequence of characterization bandpasses called “the biosignature decision tree”. The idea is to do observations in a sequence which most rapidly identifies Earth-like biospheres during each geologic eon: The Archean, Proterozoic and Phanerozoic Earth.

Currently, the decision tree begins with the spectra acquired in step (1), which searches for the $0.94\ \mu\text{m}$ water vapor feature. The decision tree suggests this same observation should be used to detect a methane rich atmosphere, analogous to the Archean Earth’s. If methane is detected, then further targeted observations will aim to confirm the presence of an Archean Earth-like biosphere.

However, the bandpass extent, spectral resolution ($R = \frac{\lambda}{\Delta\lambda}$), and signal-to-noise ratio (SNR) required to detect methane with the spectra acquired in phase (1) is currently not known. We do not know the instrument requirements in order to carry out the first step of the biosignature decision tree.

To address this problem, I perform atmospheric retrievals on synthetic LUVex spectra of an Archean Earth twin. All retrieval use a single photometric observation at 0.5 to $0.6\ \mu\text{m}$, and a single spectroscopy bandpass which encompasses the $0.94\ \mu\text{m}$ water feature. My goal is to determine the bandpass extent, spectral resolution, and SNR required to detect methane at the first step of “the biosignature decision tree” for a “nominal” Archean Earth twin.

2 Methods and Results

We do synthetic retrievals on the “nominal” Archean Earth twin containing 455 ppm CH_4 (Figure 1). We produced this atmosphere using a photochemical model with boundary conditions drawn from the literature (Kharecha, Kasting, and Siefert 2005; Catling and Zahnle 2020). For comparison, the Archean Earth could have had between ~ 100 ppm and $\sim 1\%$ methane (Catling and Zahnle 2020). Values greater than ~ 2000 ppm require either (1) biological fluxes that are challenging to reconcile with ecosystem modeling (Thompson et al. 2022), or (2) hydrogen escape at a rate lower than the diffusion limited rate (Kharecha, Kasting, and Siefert 2005; Tian et al. 2005).

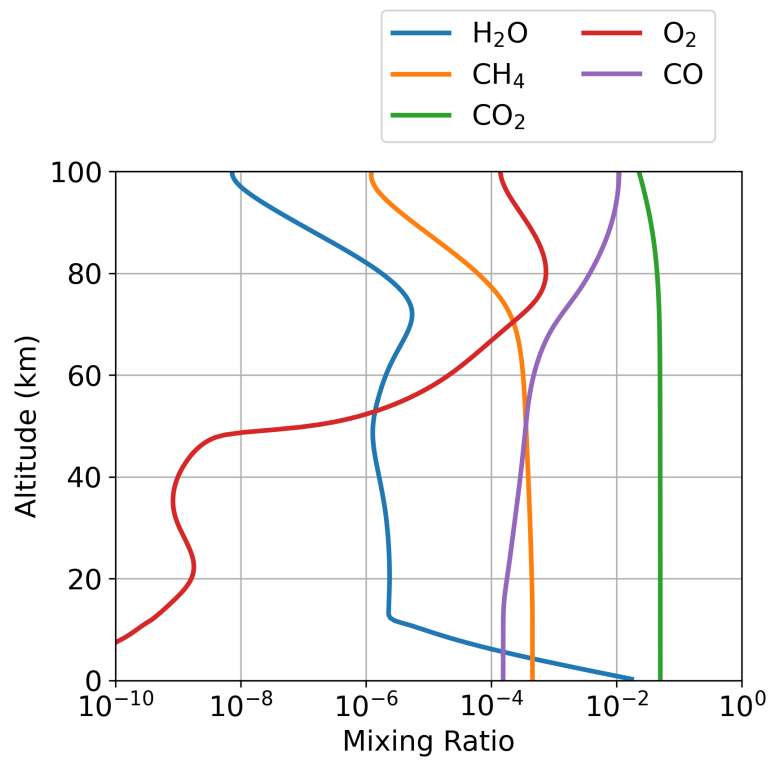


Figure 1: A nominal Archean Earth atmosphere.

This nominal Archean atmosphere is not rich with hydrocarbon aerosols because we assume $\text{CO}_2 = 5\%$, a value consistent with models of the geologic carbon cycle (Krissansen-Totton, Arney, and Catling 2018). Hydrocarbon aerosols do not form until $\text{CH}_4/\text{CO}_2 \gtrsim 0.1$. Additionally, we assume a temperature profile identical to Modern Earth in the troposphere and isothermal above the tropopause. Since our photochemical model assumes water saturation in the troposphere, our water column abundance, and therefore its spectral characteristics, should be approximately equal to Modern Earth’s.

Figure 2 shows the planet’s full phase reflectance spectrum. Grey shading indicates the approximate wavelengths where we will consider synthetic photometric and spectroscopy observations. The spectroscopic bandpass that ends at $1 \mu\text{m}$ contains about one and a half methane features on either side of the $0.94 \mu\text{m}$ water feature.

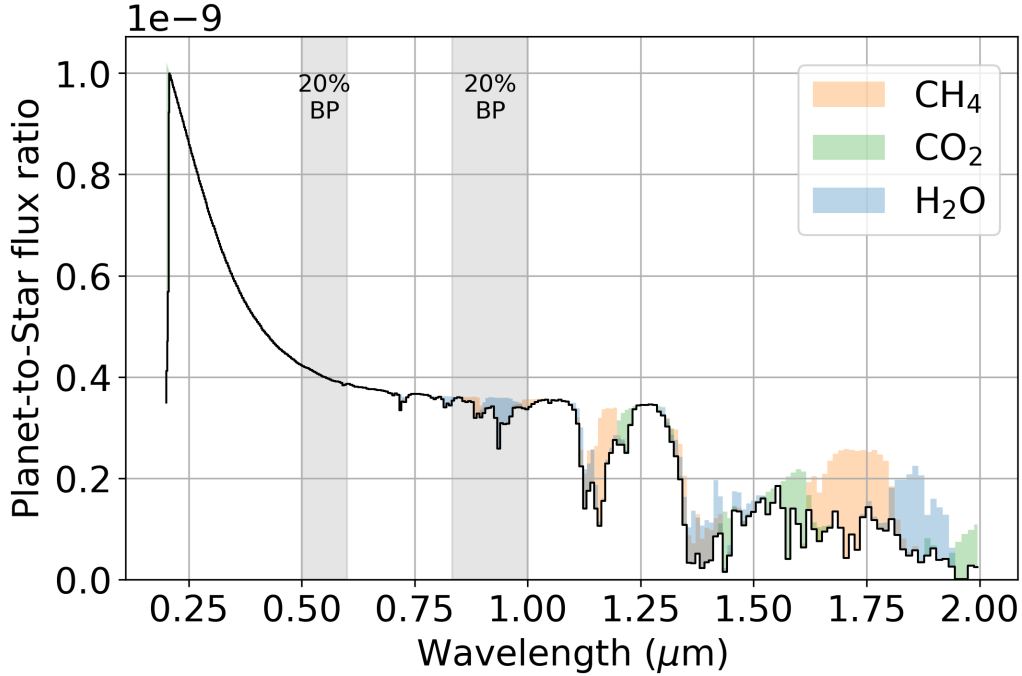


Figure 2: Full phase reflectance spectrum of a nominal Archean Earth atmosphere.

Figure 3 is identical to Figure 2, except it shows one example of the synthetic data that we do atmospheric retrievals on later in the text. This

example has one photometric observation between 0.5 and 0.6 μm with $\text{SNR} = 7$ at 0.98 μm , and one 20% spectroscopic bandpass that terminates at 1 μm with $R = 140$, and $\text{SNR} = 20$.

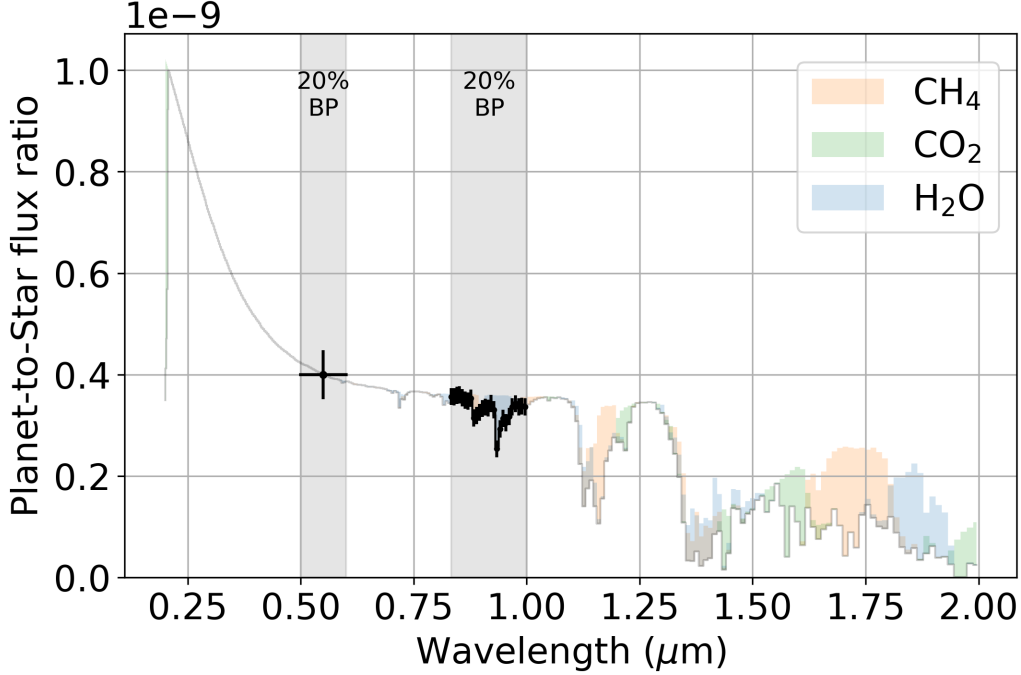


Figure 3: One of synthetic observations used in retrievals. The bandpass that terminates at 1 μm is $R = 140$, and $\text{SNR} = 20$.

We performed 24 atmospheric retrievals on synthetic data similar to those shown in Figure 3. For all retrievals we consider one photometric observation between 0.5 and 0.6 μm with $\text{SNR} = 7$, and one spectroscopic bandpass that terminates at 1 μm . For the spectroscopic observation, we consider 15%, 20%, and 25% bandpasses, $R = [70, 140]$, and $\text{SNR} = [5, 10, 15, 20]$ (for 0.98 μm). We assume the bandpass can not go beyond 1 μm , because the visible channel of the LUVex coronagraph can not operate beyond this wavelength. We neglect observations that might be made with LUVex’s near infrared channel. We retrieve N_2 , O_2 , H_2O , CO_2 , O_3 , CO , CH_4 , H_2 , surface pressure, surface albedo, planet radius, planet gravity, and several cloud properties. We assume either log-uniform or linear-uniform priors for all parameters.

Figure 4 shows retrieved methane posterior distributions for all bandpass

extents, R , and SNR. A weak methane detection requires $\text{SNR} = 20$, either $R = 70$ or $R = 140$, and a 20% or 25% bandpass. The exception is the $\text{SNR} = 20$, $R = 140$, and 15% bandpass case in the lower left-hand plot, which also has a weak methane detection. A key result is that $\text{SNR} = 20$ appears to be required for even a weak methane detection.

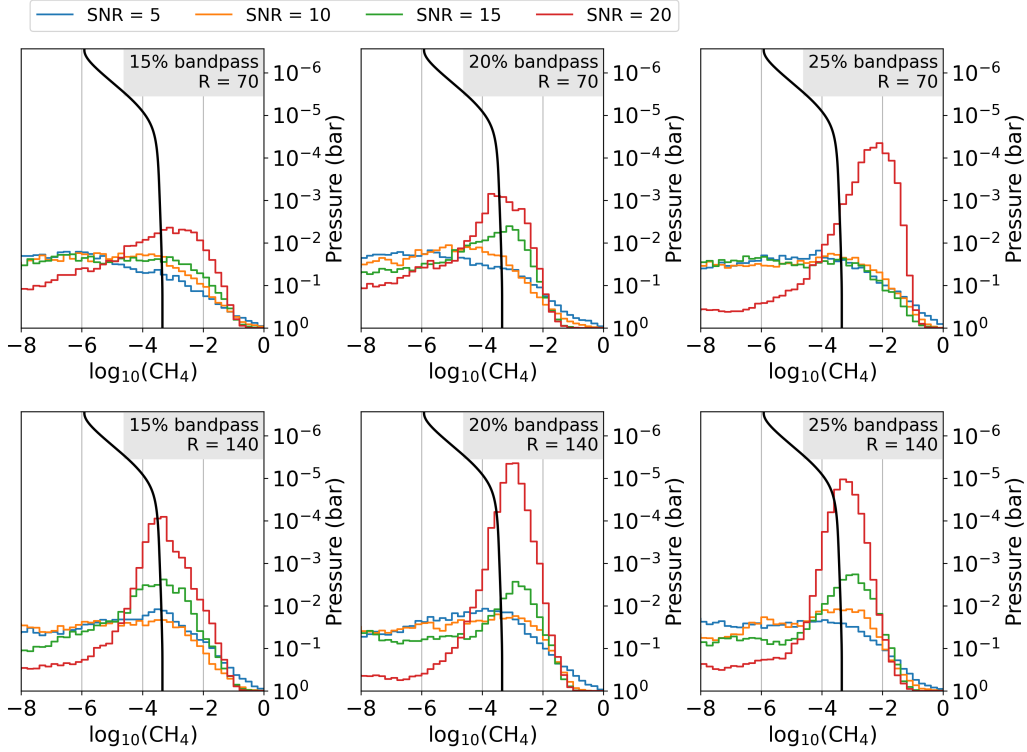


Figure 4: Retrieved methane posterior distributions for different bandpass extent, R , and SNR. The black line in each plot shows the true value as a function of atmospheric pressure.

Figure 5 shows the water vapor posterior distribution for all retrievals. Here, we find that $\text{SNR} = 10$ or greater, at any resolution and bandpass extent is sufficient for a weak water vapor detection. The LUVOIR final report says, “we require $\text{SNR} = 5$ on the continuum at $R = 70$ for water vapor detection.” We find that perhaps slightly higher than $\text{SNR} = 5$ is required for weakly detect water vapor. This result is likely very sensitive to the surface temperature which could vary significantly for habitable planets (here we

assume a surface temperature of 288 K).

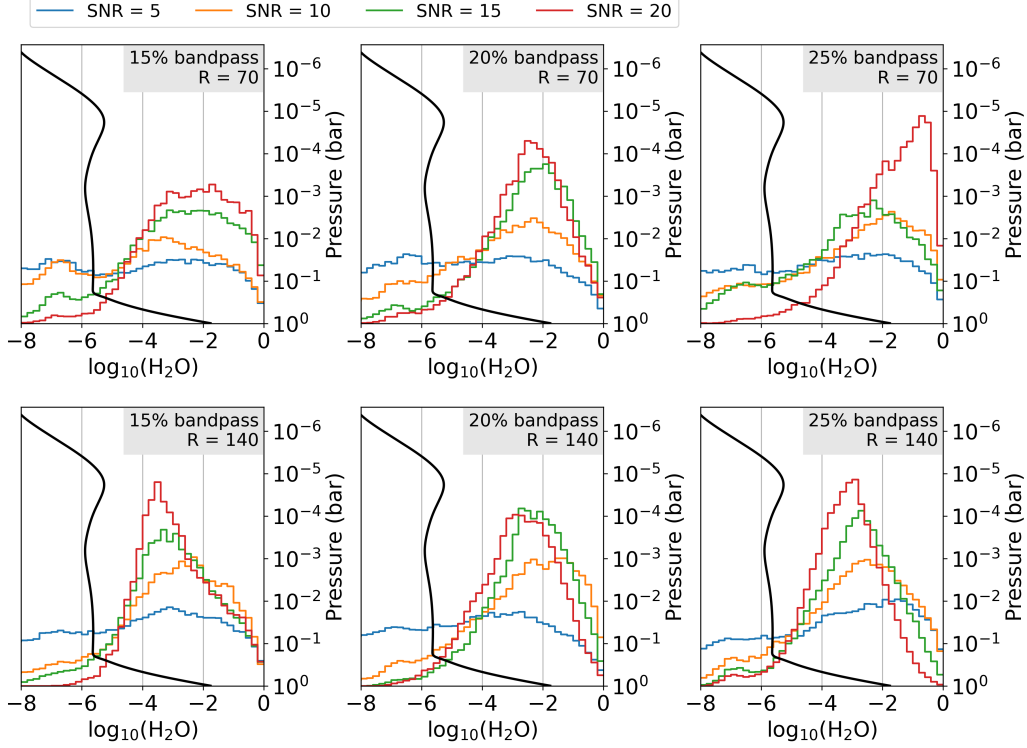


Figure 5: Retrieved H_2O posterior distributions for different bandpass extent, R , and SNR. The black line in each plot shows the true value as a function of atmospheric pressure.

All retrievals are mostly agnostic about the CO , CO_2 , and O_2 concentrations, surface gravity, and surface albedo. A N_2 background atmosphere is favored over a H_2 atmosphere.

Interestingly, the retrieval disfavors O_3 . The single photometric observation at ~ 550 nm can potentially indirectly rule out a O_2 rich atmosphere, especially if photometry SNR is closer to 5.

References

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