NON-DETECTION OF O₂/O₃ INFORMS FREQUENCY OF EARTH-LIKE PLANETS
WITH LUVOIR BUT NOT HABEX

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ABSTRACT

A critical question in the search for extraterrestrial life is whether exoEarths are Earth-like, in that they host life that progressively oxygenates their atmospheres roughly following Earth’s oxygenation history. This question could be answered statistically by searching for O₂ and O₃ on exoEarths detected by HabEx or LUVOIR. The point of this paper is to compare the ability of HabEx and LUVOIR to prevent a false negative answer to this question, in which we do not detect O₂ or O₃ on any planet even if all exoEarths are Earth-like. Our approach is to assign O₂ and O₃ values drawn from Earth’s history to a distribution of detectable exoEarths and determine whether O₂ and O₃ would be detectable using the Planetary Spectrum Generator. We find that if exoEarths tend to be Earth-like, we expect to detect O₃ with a LUVOIR-sized instrument. We also find that LUVOIR is unlikely to have a false negative scenario in the context of searching for Earth-like life on its targeted exoEarths. Because of that, if LUVOIR does not detect O₂ or O₃ on any exoEarths, we will be able to constrain the maximum number of exoEarths that could be Earth-like. In contrast, we find that even if all exoEarths are Earth-like, HabEx has up to a 22% chance of not detecting O₂ or O₃ on any of them. This is because HabEx will detect less planets and cannot reliably detect O₂ and O₃ at all potential Proterozoic levels. This is a strong argument for building a larger telescope such as LUVOIR if we want to determine whether exoEarths tend to be Earth-like.

1. INTRODUCTION

The past decade has been incredibly productive in exoplanet research, with more than 2500 exoplanets confirmed by the NASA’s Kepler and K2 missions. Of these, at least 30 planets with radii less than twice Earth’s radius were found orbiting in the habitable zone of their star (e.g., Burke et al. 2015; Dressing & Charbonneau 2015). More recently, a number of Earth-sized exoplanets have been found orbiting in the habitable zone of nearby stars (e.g., Gillon et al. 2017; Dittmann et al. 2017). These are prime targets for future instruments to study in more detail and determine whether they are truly habitable, or even inhabited (e.g., Kreidberg & Loeb 2016; Meadows et al. 2018b). NASA’s upcoming James Webb Space Telescope should dramatically increase our ability to find and characterize terrestrial exoplanets, but all will be orbiting M-stars (e.g., Deming et al. 2009; Cowan et al. 2015). The next generation of proposed instruments for the NASA Astronomy and Astrophysics Decadal Survey includes two space-based telescopes (HabEx Gaudi et al. 2020 and LUVOIR The LUVOIR Team et al. 2019) that will allow us to characterize the atmospheres of habitable zone planets orbiting Sun-like stars via direct imaging.

Life can have a measurable impact on the composition of its host planet’s atmosphere. A long-standing goal in astrobiology is to spectrally determine the presence of life via biosignatures in the atmosphere (Schwieterman...
et al. 2018). Several potential biosignatures have been proposed, such as detecting trace amounts of biologically derived molecules (e.g., Seager et al. 2005; Meadows 2008; Seager & Deming 2010; Seager et al. 2016), measuring thermodynamic chemical disequilibrium between atmospheric species (Lovelock 1965; Krissansen-Totton et al. 2018), observing of a “red-edge” in the atmospheric spectrum (Seager et al. 2005), and detecting seasonal variation (Olson et al. 2018b). Here, we focus on perhaps the most robust biosignatures, O₂ and O₃ (e.g., Owen 1980; Sagan et al. 1993; Des Marais et al. 2002; Meadows 2008, 2017; Schwieterman et al. 2018). We find that O₃ is always easier to detect than O₂, so we expect that O₃ is the main signal for an oxygenated atmosphere that will be used in future space telescope missions.

Though extensive and ongoing work is being done to determine abiotic sources of O₂ (Harman et al. 2015; Tian et al. 2014; Meadows 2017), most potential “false-positives” scenarios explored in the literature so far occur for either M-dwarf planets or planets that have since gone through a moist or runaway greenhouse phase, rendering them outside the classical habitable zone. False positive scenarios for Sun-like star planets with an Earth-like inventory of non-condensing gases have not yet been identified (Wordsworth & Pierrehumbert 2014; Meadows et al. 2018a; Harman et al. 2018), therefore we expect that we will be able to interpret O₂/O₃ detections confidently within their broader chemical and planetary context. Regardless, false negatives are not relevant to this work as our primary concern is to determine what conclusions could be drawn from a potential null detection of O₂ and/or O₃ on any of the detected exoEarths.

As future instruments are being launched and developed, the consensus is that planets that are Earth-sized, terrestrial, and orbiting in the habitable zone of their stars are great targets for the search for life. We will refer to Earth-sized habitable zone planets as “exoEarths”, although this name does not indicate that they are “Earth-like.” We will call an “Earth-like planet” an exoEarth that develops Earth-like O₂-producing life that oxygenates its atmosphere roughly following Earth’s oxygenation history. We will refer to the fraction of exoEarths that are Earth-like as fₑ. If exoEarths are generally unlikely to be Earth-like (low fₑ), it could either mean that they usually do not originate life in the first place, or that although they do originate life, O₂ levels rarely increase past Archean-like levels (either because oxygenic photosynthesis is rare or because oxygenic photosynthesis does not always manifest as planetary oxygenation). In both scenarios we will not detect O₂/O₃.

The question we are trying to answer is: Could HabEx and/or LUVOIR determine whether it is common for exoEarths to be Earth-like?

A critical consideration in this work is the possibility of mission false negatives (Reinhard et al. 2017), that is, cases where it is common for exoEarths to be Earth-like but we do not detect O₂/O₃ on any of them. We will be adopting a statistical approach to address this problem (Bean et al. 2017; Checlair et al. 2019; Bixel & Apai 2020). This means that we will not investigate false negatives on particular planets. Instead, we will try to determine whether there might be false negatives for a particular mission based on all of the information that we can gain from all of the exoEarths that this mission can be expected to observe. Even with a large sample of exoEarths, we may not find evidence of life with either LUVOIR or HabEx if the origination of life is uncommon or if exoEarths do not generally develop oxygenic photosynthesis. The frequency of life origination on habitable planets is highly uncertain (e.g., Sandberg et al. 2018), so this is a scenario that should be seriously considered. Because it is possible that Earth-like exoEarths are very rare, we want to design an instrument that would actually indicate this, rather than possibly being a false negative scenario. Using a statistical methodology with future direct imaging instruments will maximize the scientific return of these missions by allowing us to test theories of planetary habitability. This article focuses on statistically testing whether exoEarths are generally Earth-like, which necessitates a large enough sample of exoEarths so that false negative scenarios are unlikely.

This paper is organized as follows. In Section 2 we outline how we determine the number of exoEarths on which LUVOIR and HabEx could detect Earth-like life. In Section 3 we first present the integration times necessary for LUVOIR and HabEx to detect O₂ and O₃ at 5-σ. We then present our main results: the number of exoEarths on which LUVOIR and HabEx could detect Earth-like life. We end that section by discussing how we could use these observations to constrain the fraction, fₑ, of exoEarths that are Earth-like. In Section 4 we discuss some implications and caveats of our work, and we summarize results in Section 5.

2. METHODS

2.1. Overview

To estimate the distribution of the number of detected Earth-like exoEarths, we perform Monte Carlo simulations where we consider an ensemble of many repeated HabEx and LUVOIR experiments. For each Monte Carlo realization, we draw the number of planets, Nₚ, detected by each instrument and we assign to each de-
nected planet a distance from Earth and an age that are used to determine whether O$_2$ and O$_3$ are detectable on the planet. Below, we first explain how we draw $N_p$ and then we explain how we draw age and distance.

We consider two different telescope designs: 15 m segmented on-axis LUVOIR and 4 m monolith off-axis HabEx. We choose these designs because they bracket the range of reasonably likely space-based direct imaging missions over the next few decades. We use the results of Stark et al. (2019) for the number of exoEarths candidates, $N_p$, expected for each telescope design. The distribution of $N_p$ for both LUVOIR and HabEx is shown in Figure 1. We set the exposure time to 100 hours per planet.

For each Monte Carlo realization, we first draw a value for $N_p$ from Figure 1 for each instrument. This is the number of planets that will be detected using either instrument for each Monte Carlo realization. We then draw an age for each planet from a uniform distribution between 3.8 Gyr old and 0 Gyr old, the time period during which Earth is believed to have had life (Schidlowski 1988; Dodd et al. 2017). The age we draw belongs to one of Earth’s inhabited eras: Archean (3.8-2.5 Gya, 34.2% probability of being drawn), Proterozoic (2.5-0.5 Gya, 51.5% probability of being drawn), Phanerozoic (0.5-0 Gya, 14.3% probability of being drawn). We then draw a distance in parsecs for each of these $N_p$ planets. We draw these distances from a list of targets provided by Chris Stark (Stark et al. 2019), weighted by the habitable zone yield estimates, $\eta_{\text{earth}}$, for each target. Considering the planet’s era and distance, we calculate the Signal-to-Noise Ratio (SNR) for O$_2$/O$_3$ detections with each telescope design given 100 hours integration time. We define a detectability SNR threshold of 5.0 for O$_2$ and/or O$_3$ to be considered detectable, and we count the number of planets on which this condition is met. We find that the SNR is always higher for O$_3$. We repeat this for $10^7$ Monte Carlo realizations.

An important assumption we make is that exoEarths that are Earth-like develop life and atmospheric O$_2$ following the same trajectory as Earth did: Archean, Proterozoic, Phanerozoic. This means that we assume $f_E = 1$ to determine whether there are any false negative scenario under this assumption. The Archean is anoxic, which makes O$_2$/O$_3$ impossible to detect. Proterozoic O$_2$ levels are also low, though the resultant O$_3$ is potentially detectable. Phanerozoic O$_2$/O$_3$ levels are the easiest to detect. For lack of a better prior, we also assume these planets remain inhabited for the current inhabited history of the Earth of $\sim$3.8 Gyr (Schidlowski 1988; Dodd et al. 2017). This of course would depend on the planet’s position in its star’s habitable zone, as this will determine the length of time the planet remains habitable (Kopparapu et al. 2013). Earth will only remain in its own habitable zone for less than 2 Gyrs before entering a runaway greenhouse climate if we account for cloud coverage (Rushby et al. 2013). During this time, Earth’s atmospheric CO$_2$ should decrease to very low values as a result of the silicate-weathering feedback so that oxygenic photosynthesis by land plants will eventually fail (Caldeira & Kasting 1992). This would likely result in a major decrease in Earth’s atmospheric O$_2$. Considerable uncertainty remains, but atmospheric O$_2$ levels in the distant future may ultimately be more similar to the Proterozoic than Phanerozoic. Since the trajectory of Earth’s future atmospheric O$_2$ levels is highly uncertain, here we simply draw O$_2$ levels from Earth’s history.

2.2. Planetary Atmosphere simulations

We start by generating atmospheric profiles appropriate for Earth throughout its history. We do not generate profiles for the Archean, as O$_2$ and O$_3$ concentrations remain below $\sim 10^{-5}$ Present Atmospheric Level (PAL), well below detectable levels (Kasting et al. 1979; Pavlov & Kasting 2002). For the Proterozoic, we calculate the mixing ratio profiles using a one-dimensional, horizontally averaged photochemical model (Segura et al. 2007). The model has 35 long-lived chemical species, 16 short-lived chemical species, and 220 reactions. A two-stream approximation is used for radiative transfer, using a fixed zenith angle of 50 degrees. The model solves for the steady state solution at each altitude layer, accounting for chemical reactions, photolytic reactions, and vertical transport parameterized using Earth-like eddy diffusion profiles (Segura et al. 2007; Harman et al. 2015).
For our calculations, we estimate Proterozoic $O_2$ concentration as ranging from $10^{-5}$ to $10^{-1}$ PAL to survey the full range of estimates existing in the literature (Pavlov & Kasting 2002; Planavsky et al. 2014; Lyons et al. 2014; Reinhard et al. 2017; Olson et al. 2018a). Reinhard et al. (2017) and Olson et al. (2018a) also surveyed the existing literature for $CO_2$ and $CH_4$ estimates throughout Earth’s history - Archean, Proterozoic, and Phanerozoic - and placed upper and lower bounds on their abundances during each era. They argued for stricter constraints on each of these species’ mixing ratios, providing “preferred ranges” for the Proterozoic. We use the median value of those “preferred ranges” for Proterozoic $CO_2$ (2127.8 µbar) and $CH_4$ (5.1 µbar). For our Proterozoic water vapor profile, we assume a moist adiabat with a fixed relative humidity of 0.8. We then calculate the $O_3$ profile based on our background atmosphere (assumed to be 1 bar with $N_2$ as the major constituent). We then calculate the temperature profile using CLIMA, a one-dimensional radiative convective climate model (Kopparapu et al. 2013). As the Proterozoic has less $O_3$ than Modern Earth, there is a smaller temperature inversion in the stratosphere. For the Phanerozoic, we use empirical atmospheric profiles for the Modern Earth provided by NASA’s MERRA-2 dataset (Gelaro et al. 2017; Villanueva et al. 2018). We set the surface albedo to 0.3.

2.3. Simulated Observations

We use the Planetary Spectrum Generator (PSG) (Villanueva et al. (2018), https://psg.gsfc.nasa.gov) to simulate either LUVOIR (15m-mirror diameter, ECLIPS coronagraph) or HabEx (4m-mirror diameter) observations. For both instruments we set the exposure time to 100 hours. We choose LUVOIR’s and HabEx’s parameters based on their reported values in their respective Final Reports (The LUVOIR Team et al. 2019; Gaudi et al. 2020). We summarize these parameters in Table 1.

| Parameter      | LUVOIR | HabEx |
|---------------|--------|-------|
| Diameter      | 15 m   | 4 m   |
| Resolution    | 70 RP  | 140 RP|
| Wavelength Range | 0.2 – 2 µm | 0.2 – 1.8 µm |
| Exozodi Level | 4.5    | 4.5   |
| Beam          | 1 FWHM | 1 FWHM|
| Contrast      | $1 \times 10^{-10}$ | $2.5 \times 10^{-10}$ |
| IWA [λ/D]     | 3.5    | 2.4   |

2.4. Signal-to-Noise Ratio (SNR) Calculations

To calculate the SNRs, we simulate two spectra: one absorbing spectrum with all atmospheric species, and one continuum spectrum with all atmospheric species except the targeted absorber (either $O_2$ or $O_3$). We calculate the signal by taking the difference between the two spectra: the signal is higher where the absorber has a stronger absorption feature compared to the continuum. We then divide the signal by the noise that PSG simulates based on the chosen instrument to obtain the SNR as a function of wavelength, which is positive only at wavelengths where the absorbing gas absorbs. The total SNR for $O_2$ or $O_3$ is then the square root of the sum of the square of the SNRs (Lustig-Yaeger et al. 2019):

$$SNR_{total} = \sqrt{\sum_{\lambda_i} (S_{\lambda_i}/N_{\lambda_i})^2}$$  \hspace{1cm} (1)$$

where $S_{\lambda_i}$ and $N_{\lambda_i}$ are the signal and the noise for each wavelength. We scale the SNRs as being inversely proportional to distance (Stark et al. 2014). To get a better idea of whether $O_2$ and $O_3$ would be detectable in real observations for our different assumptions ($O_2$ level and cloud cover), we first calculate the integration time necessary for the total SNR to be equal to 5.0 for a planet at 5 pc (see Section 3.1). In our Monte Carlo realizations, we consider the observation of an exoEarth of a given age and at a given distance as a positive life detection if the SNR of either $O_2$ or $O_3$ is above the threshold of 5.0 (see Section 3.2), following Lustig-Yaeger et al. (2019).

3. RESULTS

3.1. Integration Times to detect $O_2$ and $O_3$ with LUVOIR and HabEx

We first present the integration times required for a 5-σ detection of $O_2$ and $O_3$ at 5 pc calculated using PSG (Villanueva et al. 2018) in Table 2 for LUVOIR and HabEx. To calculate these integration times, we first calculate the SNRs for $O_2$ and $O_3$ detection using the method outlined in Section 2.4 with an exposure time of 100 hours. We then calculate what the exposure time would have to be for these SNRs to be equal to 5.0:

$$\Delta t = 100 \text{ [hrs]} \times \left(\frac{5}{\text{SNR}}\right)^2$$  \hspace{1cm} (2)$$

We consider six different $O_2$ levels: Modern (1 PAL), and five Proterozoic estimates ($10^{-1}$ to $10^{-5}$ PAL). In all cases for both LUVOIR and HabEx, $O_3$ is easier to detect than $O_2$ due to its deep and broad feature between 0.5-0.7 µm (Chappuis bands) and between 0.2-0.3 µm (Hartley bands). Most importantly, $O_3$ is detectable...
Table 2. Integration times with LUVOIR (15 m) and HabEx (4 m) to yield a 5-σ detection of O₂ and O₃ for an Earth-like planet without clouds at 5 pc for six different O₂ levels.

| O₂ level          | 15 m LUVOIR | 4 m HabEx |
|-------------------|-------------|-----------|
| O₂ = 1 PAL        | O₂: 0.8 hr  | O₂: 8 hrs |
|                   | O₃: 0.2 hr  | O₃: 3 hrs |
| O₂ = 10⁻¹ PAL     | O₂: 10 hrs | O₂: 44 hrs |
|                   | O₃: 0.4 hr  | O₃: 11 hrs |
| O₂ = 10⁻² PAL     | O₂: 133 hrs| O₂: 460 hrs|
|                   | O₃: 0.8 hr  | O₃: 100 hrs|
| O₂ = 10⁻³ PAL     | O₂: 2342 hrs| O₂: 7713 hrs|
|                   | O₃: 1.8 hrs | O₃: 268 hrs |
| O₂ = 10⁻⁴ PAL     | O₂: 113,843 hrs | O₂: 366,012 hrs |
|                   | O₃: 11 hrs  | O₃: 17,376 hrs |
| O₂ = 10⁻⁵ PAL     | O₂: 1 x 10⁷ hrs | O₂: 3.3 x 10⁷ hrs |
|                   | O₃: 478 hrs | O₃: 3.6 x 10⁶ hrs |

at 5-σ with LUVOIR in under 100 hours even at very low Proterozoic O₂ levels (down to 10⁻⁴ PAL). With HabEx, detecting O₂ at 5 pc is difficult (>100 hours) for Proterozoic O₂ levels below 0.01 PAL. We note here that the HabEx integration times we calculated for O₂ and O₃ (without clouds) are ~1-4 orders of magnitude larger than reported in the HabEx report depending on the O₂ level (Gaudi et al. (2020), see their Figure 3.3-7). We investigated this discrepancy and discuss it further in the Discussion and the Appendix.

3.2. Likelihood of detecting life with LUVOIR and HabEx

We present the probability distributions of total Earth-like life detections for LUVOIR (left columns) and HabEx (right columns) in Figure 2. As described in Section 2, we calculate the SNR of O₂ and O₃ for a given exoEarth at a certain distance and with a certain level of O₂ based on its age drawn from a uniform distribution. If either of these SNRs is above the threshold of 5.0, we consider that exoEarth a positive life detection. We note here that since O₃ is easier to detect than O₂ in all cases we considered (see Tables 2), O₃ detectability is the limiting factor in determining whether Earth-like life is detectable on a given exoEarth. ExoEarths can either have Archean (34.2% probability), Proterozoic (51.5% probability), or modern (14.3% probability) levels of O₂ and O₃. We consider Archean levels undetectable, and therefore if an exoEarth is drawn to be of Archean age, we consider it a null detection. We assume that f_E = 1 and determine whether there are any false-negative scenario even under this assumption. We vary the Proterozoic O₃ from 10⁻⁵ to 0.1 PAL.

For LUVOIR, for Proterozoic levels of O₂ equal to or larger than 10⁻³ PAL, O₃ is detectable for exoEarths at all target distances for both modern and Proterozoic levels. Because of this, the first three rows of Figure 2 show the same distribution. The reason the distribution is offset from 62 (Figure 1) is that O₂ and O₃ are undetectable for exoEarths in an Archean era and so all exoEarths drawn to be of Archean age will correspond to a null detection of life. For these three levels of Proterozoic O₂, we find that LUVOIR has a 95% chance of detecting 29-54 exoEarths. At Proterozoic O₂ levels of 10⁻⁴ and 10⁻⁵ PAL, O₃ is only detectable on exoEarths at close distances (<15.1 pc at 10⁻⁴ PAL and <2.3 pc at 10⁻⁵ PAL), and therefore the distribution shifts towards zero due to the exoEarths that are further away and drawn to be of Proterozoic age. We find that LUVOIR has a 95% chance of detecting 14-32 Earth-like exoEarths for Proterozoic levels of 10⁻⁴ PAL, and 4-15 Earth-like exoEarths for Proterozoic levels of 10⁻⁵ PAL. In the first four cases (Proterozoic O₂ between 0.1-10⁻⁴ PAL), the distribution of the number of exoEarths that have detectable O₂ and/or O₃ is well above zero. For the case with Proterozoic levels of 10⁻⁵ PAL, the curve’s end member is above zero with 2 as the smallest number of detected Earth-like exoEarths. There is therefore no false negative scenario for LUVOIR as a mission if f_E = 1: Earth-like life will be detected on a number of exoEarths if it commonly develops on them.

For HabEx, O₃ is detectable on exoEarths in their modern eras at all target distances. In their Proterozoic eras, O₃ is only detectable if they are nearby enough: <14.8 pc for 0.1 PAL, <5.0 pc for 10⁻² PAL, and <3.1 pc for 10⁻³ PAL. For lower Proterozoic O₂ levels (10⁻⁴ and 10⁻⁵ PAL), O₃ cannot be detected on any exoEarth in their Proterozoic era (and therefore these cases show the same distribution). We find that HabEx has a 95% chance of detecting 2-12 Earth-like exoEarths for Proterozoic levels of 0.1 PAL, 0-7 for 10⁻² PAL, 0-5 for 10⁻³ PAL, and 0-4 for 10⁻⁴ and 10⁻⁵ PAL. For all four cases where the Proterozoic O₂ level is lower than 0.1 PAL, HabEx has a false negative scenario where we do not detect life on any of the exoEarths we observe despite the fact that oxygen-producing life exists. That false negative probability depends on the assumed Proterozoic O₂ level, and in the cases we considered it is: 0% for 10⁻¹, 5% for 10⁻², 18% for 10⁻³, and 22% for 10⁻⁴ and 10⁻⁵ PAL. We summarize these false negative probabilities for HabEx in Table 3.

3.2.1. Takeaway
Figure 2. For LUVOIR, there are no false negative scenarios and Earth-like life will be detected on a number of exoEarths if it commonly develops on them. For Proterozoic O\textsubscript{2} levels below 0.1 PAL, there are false negative scenarios for HabEx (with probabilities of 5\% for $10^{-2}$, 18\% for $10^{-3}$, and 22\% for $\leq 10^{-4}$ PAL of O\textsubscript{2}). The plots show the probability distributions of the number of exoEarths on which an O\textsubscript{2} and/or O\textsubscript{3} signature could be detected by a 15m segmented on-axis LUVOIR (left) and a 4m monolith off-axis HabEx (right) assuming that all exoEarths are Earth-like. If the distribution reaches zero, there is a non-zero false negative probability: O\textsubscript{2} and/or O\textsubscript{3} are undetectable despite the existence of Earth-like life. We draw an age for exoEarths between Archean, Proterozoic, and modern eras, and assume Archean O\textsubscript{2} and O\textsubscript{3} levels are undetectable. Proterozoic O\textsubscript{2} concentrations range between $10^{-5}$ and 0.1 PAL. The grey dotted lines represent the 95\% confidence interval.
The main difference between LUVOIR and HabEx in the context of the search for Earth-like life is the possibility of a false negative scenario. With LUVOIR, we expect to detect Earth-like life if it is common as there are no false negative scenarios for the mission collectively when \( f_E = 1 \). However, even if Earth-like life is common on all the exoEarths we observe, there is a nonzero probability of up to 22% of not detecting it with HabEx. That probability is greater for lower Proterozoic \( O_2 \) levels. The only case where HabEx does not have a false negative scenario is that for which the Proterozoic \( O_2 \) level is 0.1 PAL (Figure 2, top right panel). This is an important conclusion as it introduces the possibility of not detecting any \( O_2/O_3 \) on exoEarths with HabEx, even in the optimistic scenario where they all have originated Earth-like life. In addition to this, it makes any inference about the fraction \( f_E \) of exoEarths that are Earth-like impossible, as a null detection with HabEx could be caused by a false negative scenario.

**Table 3. Probability of a false negative scenario with 4 m HabEx for different assumptions of Proterozoic \( O_2 \) concentrations.** The probability of a false negative scenario with 15 m LUVOIR is 0% in all cases (not shown in table). We draw a distance from the mission target list and an age (Archean: 34.2% probability, Proterozoic: 51.5% probability, or modern: 14.3% probability) for each exoEarth observed. A false negative scenario is defined as not detecting \( O_2/O_3 \) on any of the observed exoEarths even though we assume they have originated life and follow Earth’s oxygenation history.

| \( O_2 \) concentration (PAL) | Probability of a false negative scenario |
|-------------------------------|----------------------------------------|
| \( 10^{-4} \)                  | 0%                                      |
| \( 10^{-2} \)                  | 5%                                      |
| \( 10^{-3} \)                  | 18%                                     |
| \( 10^{-4} \)                  | 22%                                     |
| \( 10^{-5} \)                  | 22%                                     |

3.3. *Using observations to infer the fraction \( f_E \) of exoEarths that are Earth-like*

In the highly likely scenario that only a fraction \( f_E \) of exoEarths are actually Earth-like, the number of planets on which we detect \( O_2/O_3 \) will be decreased by a factor \( f_E \). For example, if only 10% of exoEarths are Earth-like \( (f_E = 0.1) \), the peak of Figure 2’s first row panel for LUVOIR will shift from 40 to 4. For HabEx the peak of all panels will shift towards zero to create distributions with peaks at zero, making it unlikely that we will be able to detect Earth-like life with HabEx if \( f_E \) is less than 1. With a LUVOIR-like instrument that lacks false negatives for \( f_E = 1 \), our observations will inform us on an approximate value of \( f_E \) whether or not we detect life. This would be an important scientific result, and is a strong argument for choosing a direct imaging mission with a larger aperture mirror that could detect a greater number of planets. If Earth-like life exists, we are likely to detect it with LUVOIR for a sufficiently large \( f_E \), and any nonzero detection would allow us to deduce an approximate value of \( f_E \) given the number of planets observed. A null result would also inform us that \( f_E \) is likely low, and so exoEarths are unlikely to be Earth-like. In our optimistic case (Proterozoic levels of \( O_2 \) equal to 10^{-5} PAL), a null result with LUVOIR would mean that \( f_E \) is lower than \( \sim 4\% \), which is the factor needed to make the smallest end member of the distribution lower than 1. Alternatively, in our pessimistic case (Proterozoic \( O_2 \) levels equal to \( 10^{-15} \) PAL), a null result would mean that \( f_E \) is lower than 49%. Therefore, based on the cases we considered, a null result with LUVOIR would infer that \( f_E \)’s maximum possible value is 49%. This also implies that if Earth-like life exists, we are likely to detect it with LUVOIR for \( f_E > \sim 0.04–0.5 \).

4. **DISCUSSION**

The main finding of this work is that if exoEarths are likely to be Earth-like in that they develop Earth-like oxygenic photosynthesis that oxygenates their atmosphere, we should find life (detect \( O_2/O_3 \)) with a LUVOIR-sized instrument. This means that if we do not detect \( O_3 \) on any exoEarths with LUVOIR, we can conclude that Earth-like life is not common. In contrast, a HabEx-sized telescope would have up to a 22% chance of a false negative where Earth-like life is common but we do not detect it. If we find life on a number of exoEarths that is lower than the number we would expect if \( f_E = 1 \), we will gain a better understanding of the fraction of exoEarths that are actually Earth-like \( (f_E) \). Whether or not we detect life with LUVOIR, our observations will inform us on an approximate value for \( f_E \), which will not be the case for a smaller instrument. This is a strong argument for choosing a larger-aperture telescope.

The HabEx integration times we calculated for \( O_2 \) and \( O_3 \) contradict those reported in the HabEx report (Gaudi et al. 2020). We find that the integration times necessary to detect \( O_2 \) and \( O_3 \) with HabEx are 1–4 orders of magnitude larger than in their study (see their Figure 3.3-7). We investigated this discrepancy and found that the \( O_2 \) integration times reported in the HabEx report were calculated at 0.2 \( \mu \)m exclusively (where \( O_2 \) absorbs in the Herzberg continuum), and that
only O$_2$ and N$_2$ were considered in these calculations. Because of this, the difference between the continuum (N$_2$ only) and the absorption spectrum (N$_2$ and O$_2$) is large at 0.2 $\mu$m as N$_2$ does not absorb there. In Earth-like atmospheres, species such as O$_3$ and H$_2$O absorb at these short wavelengths. This minimizes the difference between the continuum spectra (without O$_2$) and the absorber spectra (with O$_2$) at 0.2 $\mu$m. Therefore, we do not expect the signal to be large at 0.2 $\mu$m for Earth-like planets. In addition to this, the noise considered in the calculations in Gaudi et al. (2020) is near zero at 0.2 $\mu$m, leading to a very large SNR and therefore a very small integration time. In comparison, the noise we use in our SNR calculation increases with decreasing wavelengths and is therefore large at 0.2 $\mu$m. On the other hand, the O$_3$ signals are only weakly affected by the non-inclusion of other species, as O$_3$ is the main absorber at small wavelengths; therefore both our and the HabEx report’s signals are maximized at 0.2-0.3 $\mu$m. However, the O$_3$ integration times are similarly affected by our different noise assumptions, as the maximum SNR is achieved at 0.2-0.3 $\mu$m in the HabEx report calculations, while our maximum SNR is achieved at 0.6 $\mu$m (O$_3$ Chappuis bands).

We have also explored the impact clouds have on SNRs and integration times for O$_2$ and O$_3$ detections. We did this by using cloud mass mixing ratio profiles for Earth-like clouds from satellite data provided by NASA’s MERRA-2 dataset (Gelaro et al. 2017; Villanueva et al. 2018). We chose deep tropical convective clouds taken from Indonesia in November to represent the upper limit of extensive cloud coverage for an Earth-like planet. We found that O$_3$ detections are relatively unaffected by a cloud cover, as most of the O$_3$ column mass is found above the cloud deck (>2/3 of our O$_3$ column mass). Because of this, our results remain unchanged by the addition of a cloud deck as O$_3$ detectability is the limiting factor in determining whether Earth-like life (O$_2$/O$_3$) is detectable on a given exoEarth. Unlike O$_3$, O$_2$ detections are strongly affected by the presence of clouds. We found that the integration times needed to detect O$_2$ at 5-$\sigma$ with LUVOIR and HabEx increase by up to an order of magnitude when including tropical Earth-like clouds. In future work, we will explore the effects of clouds on O$_2$ and O$_3$ detections with HabEx and LUVOIR in 3D using the ROCKE-3D Global Climate Model (Way et al. 2017). As HabEx and LUVOIR are still mission concepts, their specifications are not yet finalized. The number of exoEarths that we can detect with either instrument depends on the set of specificities we choose from Stark et al. (2019). We chose telescope designs that have been presented in the final reports (The LUVOIR Team et al. 2019; Gaudi et al. 2020). This study was performed using a high throughput scenario for both instruments, which is likely optimistic. We considered a pessimistic scenario where we use a low throughput, and recreated Figure 1. We found that the number of exoEarths that we could detect with LUVOIR decreases from 62 to 36 and with HabEx from 10 to 8. In this low throughput scenario, the peaks of Figure 2 are shifted to the left as well. In our most pessimistic case (Proterozoic O$_2$ level of $10^{-5}$ PAL), this introduces a false negative scenario probability of 0.5% for LUVOIR, and increases that probability from 22% (in the high throughput scenario) to 31% for HabEx.

The level of O$_2$ during the Proterozoic is highly uncertain (Reinhard et al. 2017; Olson et al. 2018a), with lower and upper constraints from various geochemical records and modeling efforts that vary by four orders of magnitude from $10^{-5}$ to $10^{-1}$PAL (Pavlov & Kasting 2002; Planavsky et al. 2014; Lyons et al. 2014; Olson et al. 2018a). The lower limit on Proterozoic O$_2$ is inferred from the end of mass-independent fractionation of S isotopes in the wake of the “Great Oxidation Event.” The upper limit of $10^{-1}$ PAL comes from the observation that the deep ocean remained anoxic throughout the Proterozoic, implying that surface environments were only mildly oxygenated. Additionally, photo-chemical modeling of the Proterozoic shows that it is difficult to maintain stable O$_2$ concentrations at lower levels (Catling et al. 2007; Zahnle et al. 2006; Kump 2008). More recent work by Planavsky et al. (2014) provides an alternate upper limit that is lower than $10^{-1}$ PAL by leveraging the absence of Cr isotope fractionation in Proterozoic marine sediments to argue for $pO_2 = 10^{-5}$ PAL or lower. A number of previous studies that considered the detectability of Proterozoic oxygen remained above an O$_2$ threshold of approximately $10^{-3}$ PAL (Reinhard et al. 2017; Schwieterman et al. 2018; Gaudi et al. 2020). We considered Proterozoic O$_2$ levels as low as $10^{-5}$ PAL to span the full range of estimates existing in the literature and to allow us to consider every possible scenario in the search for Earth-like life with HabEx and LUVOIR.

Whether the origination of life is an extremely rare occurrence or common throughout the universe is a heavily debated topic. The frequency of life originating on habitable planets is highly uncertain (e.g., Sandberg et al. 2018), and we cannot use our own solar system to help constrain this frequency as the Earth is the only planet for which we know life has originated. However, the large number of exoplanets that we may be able to soon characterize with future missions offers an opportunity
to test whether the origin of life is common. If we observe a number of exoEarths and detect clearly biogenic O₂/O₃ on at least one of them, the origination of life on habitable planets must be common. Conversely, if we don’t detect O₂/O₃ with a LUVOIR-like instrument, we’ll know that exoEarths are generally unlikely to be Earth-like. This could mean that either the origination of life is very rare, or that life never develops oxygenic photosynthesis. In this scenario of null-life detection, we may be able to improve our estimate of the probability of the origination of life using a bayesian analysis similar to that of Spiegel & Turner (2012) and Kipping (2020). Future work could look at what constraints we can put on the origination of life using a bayesian analysis for different observation scenarios.

5. CONCLUSIONS

In this article, we consider the probability that HabEx and/or LUVOIR will detect life on Earth-sized habitable zone planets (exoEarths). We adopt a statistical approach to this problem. Instead of investigating false negatives on particular planets, we determine whether there might be false negatives for missions such as LUVOIR and HabEx based on all of the information that we can gain from all of the exoEarths that these missions can be expected to observe. We also consider whether these observations may inform us on the fraction of exoEarths that are Earth-like (fₑ) in that they develop Earth-like, O₂-producing life (oxygenic photosynthesis) roughly following Earth’s O₂ history. We define a positive Earth-like life detection as a detection of either O₂ or O₃ on an exoEarth orbiting a Sun-like star. The main conclusions of this article are:

1. If exoEarths are likely to be Earth-like in that they develop Earth-like O₂-producing life (oxygenic photosynthesis) following roughly the same history Earth did, we should detect O₂/O₃ with a LUVOIR-sized instrument on 29-54 exoEarths for the highest Proterozoic O₂ estimate, and 4-15 exoEarths for the lowest estimate. This would be convincing evidence that Earth-like life is common in the universe.

2. If we find life using a LUVOIR-sized instrument on a number of exoEarths that is lower than the number we would expect if fₑ = 1, we would gain a better understanding of the fraction of exoEarths that are actually Earth-like (0 < fₑ < 1). For example, it may be that only 10% (fₑ = 0.1) of exoEarths are Earth-like while the rest of them either never originated life or never evolved beyond an Archean-like level of atmospheric O₂, or that life has eventually died off.

3. LUVOIR as a mission does not have any false negative scenarios in the context of searching for Earth-like life on its targeted exoEarths. A direct consequence of this is that if we do not detect Earth-like life on any exoEarths with a LUVOIR-sized instrument, we could confidently conclude that exoEarths are not generally Earth-like: fₑ < ∼ 0.04 – 0.5. Instead, they either do not originate life, or they never build up high levels of O₂, or life has died off.

4. A smaller instrument, such as HabEx, has up to a 22% chance of a false negative scenario where we do not detect O₃ on any exoEarths even if they are all Earth-like and host O₂-producing life. Not detecting O₃ on any exoEarths with such an instrument would either indicate that exoEarths are not generally Earth-like (fₑ ∼ 0) or that even though exoEarths are typically Earth-like we happened to not detect O₂/O₃ on any of them and are in a false negative scenario. Since there would be no way to differentiate between these two scenarios, there is a danger that such an instrument would not be useful for constraining the prevalence of Earth-like life in the universe.

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APPENDIX

A. COMPARING OUR O$_2$ AND O$_3$ INTEGRATION TIMES TO THOSE OF THE HABEX REPORT

In this appendix we compare our integration time calculations for O$_2$ and O$_3$ detections on exoEarths to those reported in the HabEx report (Gaudi et al. 2020). Figure 3.3-7 in the HabEx report shows the integration times necessary to detect O$_2$ and O$_3$ at 5-$\sigma$ confidence from 5 pc away for different O$_2$ and O$_3$ concentrations. We note that these calculations do not account for the effects of clouds. We obtained the code used to calculate the integration times reported in this figure and compared its results with ours.

We begin by comparing our O$_2$ integration times to those of the HabEx report. To directly compare our calculations, we simulate observations with HabEx of an exoEarth at 5 pc and with concentrations of 100 g/cm$^2$ ($\sim$ 0.5 PAL) and 1 g/cm$^2$ ($\sim$ 0.005 PAL) of O$_2$ and set the exposure time to 1 hour. We then calculate the integration time needed for a 5-$\sigma$ detection of O$_2$ using the method outlined in Section 3.1. Based on Figure 3.3-7 of the HabEx report, at a concentration of 100 g/cm$^2$, O$_2$ would be detectable at 5-$\sigma$ with an integration time of 1.6 hours. This is much lower than what we calculate using the Planetary Spectrum Generator (28.9 hours for the 0.76 $\mu$m feature, 16.6 hours integrated over the spectrum). Part of the reason for this discrepancy is that we include other atmospheric species in our calculation of the SNR, while the calculations made to create Figure 3.3-7 in the report only include O$_2$ and N$_2$. This leads to a large difference between our calculated signals, as can be seen in Figure 3. In our case the strongest signal is at 0.76 $\mu$m (“O$_2$ A-band”, O$_2$’s strongest absorption feature in the visible), while in the HabEx report calculations the strongest signal is at $\sim$0.2 $\mu$m (where O$_2$ absorbs in the Herzberg continuum).

![Figure 3. Signals for O$_2$ detection for an Earth-like planet orbiting at 1 AU around a Sun-like star at 5 pc with an exposure time of 1 hour. Left panel: our work, including N$_2$, H$_2$O, and O$_3$ as background gases, Right panel: HabEx report, including only N$_2$ as a background gas. The signals are obtained by taking the difference between a continuum and an absorption spectrum (see Figure 4). Note that due to the different units used in each case, the signals cannot be directly compared quantitatively. The important point is that the signal is maximized at 0.76 $\mu$m (“O$_2$ A-band”) in our work, while it is maximized at 0.23 $\mu$m (Herzberg continuum) in the HabEx report.](https://example.com/figure3)

In both cases, the signal is calculated by taking the difference between a continuum and an absorption spectrum. In the case of the HabEx report, the continuum only includes N$_2$, and the absorption spectrum includes O$_2$ and N$_2$. In our work, we include other species such as O$_3$, H$_2$O, and CO$_2$. The reason this matters is that, at wavelengths shorter than 0.3 $\mu$m, solar radiation is absorbed strongly by a number of atmospheric species (especially O$_3$) and is used photochemically to break bonds, so that very little radiation gets reflected back to space even with a small concentration of any of these absorbing species. Because of this, in the HabEx report calculations there is a large difference between the continuum (where the radiation at 0.2 $\mu$m does not get absorbed by N$_2$) and the absorption spectrum (where O$_2$ absorbs all of it at 0.2 $\mu$m). In our work, the continuum already includes absorption due to other species, and therefore there is a very small difference between our continuum and our absorption features, which leads to a small SNR at 0.2 $\mu$m. This difference can be seen in Figure 4, where the left panel shows the continuum and absorption spectra we used to calculate the signal, and the right panel shows those used in the HabEx report calculations. To further verify this, we calculated our signal in the same way as the HabEx report, where the continuum
only includes N\textsubscript{2} and the absorption spectrum includes O\textsubscript{2} and N\textsubscript{2}. Similarly to the HabEx report, the signal in this case peaks at 0.2 \( \mu \text{m} \) (not shown).

Figure 4. Continuum and absorption spectra for O\textsubscript{2} detection for an Earth-like planet orbiting at 1 AU around a Sun-like star at 5 pc with an exposure time of 1 hour. Left panel: our work (geometric albedo), including N\textsubscript{2}, H\textsubscript{2}O, and O\textsubscript{3} as background gases, Right panel: HabEx report (bond albedo), including only N\textsubscript{2} as a background gas. The background gases included in our work absorb radiation strongly at <0.3 \( \mu \text{m} \), so the continuum and the absorption spectra are nearly identical at these wavelengths. In contrast, the continuum and absorption spectra from the HabEx report differ greatly at <0.3 \( \mu \text{m} \) as N\textsubscript{2} alone does not absorb there.

We compare our different noise models in Figure 5. We predict that the noise is maximized at short wavelengths (<0.4 \( \mu \text{m} \)), while in the HabEx report the noise decreases to near-zero from 0.4 to 0.2 \( \mu \text{m} \). The main reason for the steep increase in noise at <0.4 \( \mu \text{m} \) in PSG is a large decrease in stellar radiation (and thus reflected sunlight) at these wavelengths, leading to reduced photon statistics. PSG employs the LASP Interactive Solar Irradiance Data Center and the MUSCLES Treasury Survey (France et al. 2016) to estimate the stellar UV fluxes shorter than 0.4 \( \mu \text{m} \). Atomic and ionic emissions are not considered, and only absorptions in reflected sunlight are assumed. Because of this large increase in noise at <0.4\( \mu \text{m} \), the SNR in our case will always be very small at low wavelengths, even if the signal were large there. Our SNRs can be directly compared after being normalized by a scaling factor and are shown in Figure 6. The SNR for the HabEx report is maximum at \( \sim 0.2 \) \( \mu \text{m} \), while in our case the maximum SNR is at 0.76 \( \mu \text{m} \). The SNRs are similar at all wavelengths >0.3 \( \mu \text{m} \). The peak at \( \sim 0.2 \) \( \mu \text{m} \) for the HabEx report’s SNR is due to the signal being maximized and the noise being near zero at that wavelength.

Figure 5. Noise for O\textsubscript{2} detection with HabEx for an Earth-like planet orbiting at 1 AU around a Sun-like star at 5 pc with an exposure time of 1 hour. Left panel: our work, Right panel: HabEx report. Note that due to the different units used in each case, the noise in each panel cannot be directly compared quantitatively. The main difference between the two panels is that in our work the noise sharply increases from 0.4 to 0.2 \( \mu \text{m} \), while in the HabEx report the noise decreases sharply from 0.4 to 0.2 \( \mu \text{m} \) and is near-zero at 0.2 \( \mu \text{m} \)

In future direct imaging observations, confirming an O\textsubscript{2} detection at wavelengths <0.3 \( \mu \text{m} \) may be difficult if other absorbing species such as H\textsubscript{2}O, CO\textsubscript{2}, or O\textsubscript{3} (particularly O\textsubscript{3}) are present in the atmosphere of the exoplanet, and may
be impossible based on the large amount of noise at such low wavelengths. However, in Figure 3.3-7 of the HabEx report the integration times reported are those calculated for whichever wavelength has the strongest SNR. In the case of O$_2$, because only N$_2$ and O$_2$ were considered, that wavelength is always 0.2 $\mu$m. This leads to small integration times as the signal at 0.2 $\mu$m is large since no other atmospheric species are considered and the noise there is near-zero. The integration time calculated for the 0.76 $\mu$m feature at this O$_2$ concentration is comparatively much larger (30.3 hrs instead of 1.6 hrs). In our work, we calculate the integration time to detect O$_2$ at 5-$\sigma$ to be 28.9 hrs at 0.76 $\mu$m, and 16.6 hrs integrated over the spectrum. These values are respectively a factor of 18 and 10 times larger than reported in Figure 3.3-7 of the HabEx report. We note that for the 0.76 $\mu$m O$_2$ feature, the integration time we calculate (28.9 hrs) and that of the HabEx report (30.3 hrs) are similar.

In the case of O$_3$, our signals are large at shorter wavelengths (0.2-0.3 $\mu$m), similar to those of the HabEx report, because O$_3$ is the main absorber at these wavelengths. However, our noise model predicts a large amount of noise at <0.3 $\mu$m, so the SNR is very small there. Because of this, the SNR of O$_3$ detections is maximized at $\sim$0.6 $\mu$m in our calculations. In comparison, it is maximized at 0.2-0.3 $\mu$m in the HabEx report calculations as their noise is near zero at <0.3 $\mu$m. As a result, our integration times for O$_3$ are 1-4 orders of magnitude larger than those in the HabEx report, depending on the O$_3$ level.

Another reason that O$_2$ might be more difficult to detect than what is reported in the HabEx report is that clouds were not taken into consideration. We tested the effect of clouds on the integration time required for a 5-$\sigma$ detection at 5 pc for two types of clouds: tropical Earth-like clouds (Indonesia in November) and desert Earth-like clouds (Algeria in July). At an O$_2$ level of 100 g/cm$^2$, we find that the integration time required to detect O$_2$ is 36.5 hrs integrated over the spectrum (53.4 hrs for the 0.76 $\mu$m band) when using tropical clouds, and 18.0 hrs integrated over the spectrum (31.2 hrs for the 0.76 $\mu$m band) when using desert clouds (similar integration time as the no-cloud case). The integration time for O$_3$ detections is only weakly affected by the presence of clouds, as most of the O$_3$ column mass is present above the cloud deck. At an O$_2$ level of 1 g/cm$^2$, the effect of tropical clouds is stronger. We find that the integration time required to detect O$_2$ is 9915 hrs integrated over the spectrum (12,374 hrs for the 0.76 $\mu$m band) when using tropical clouds, and 1564 hrs integrated over the spectrum (2005 hrs for the 0.76 $\mu$m band) when using desert clouds. Earth-like tropical clouds could therefore increase the integration time needed to detect O$_2$ by a factor of 2 for O$_2$ levels of 100 g/cm$^2$ and by a factor of 8 for O$_2$ levels of 1 g/cm$^2$.

To summarize, we find that the integration times necessary to detect O$_2$ on an Earth-like planet at 5 pc are 1-4 orders of magnitude larger than those reported in the HabEx report, depending on the O$_2$ level. Similarly, we find that O$_3$ integration times are 1-4 orders of magnitude larger than those reported in the HabEx report, depending on the O$_3$ level.
Figure 7. Integration times necessary to detect O$_2$ and O$_3$ at 5-$\sigma$ as a function of O$_2$/O$_3$ column masses, for an Earth-like planet orbiting at 1 AU around a Sun-like star at 5 pc (solid), 10 pc (dashed), and 15 pc (dotted). HabEx data are taken from Figure 3.3-7 in the HabEx report (Gaudi et al. 2020). a) Left: O$_2$ integration times. Black lines: HabEx report calculations made for the 0.2$\mu$m O$_2$ feature with only N$_2$ and O$_2$ considered. Red lines: Our calculations for O$_2$ integration time integrated over the spectrum with all atmospheric species considered and no cloud cover. b) Right: O$_3$ integration times. Black lines: HabEx report calculations made for the $\sim$0.2-0.3$\mu$m O$_3$ feature with only N$_2$ and O$_3$ considered. Red lines: Our calculations for O$_3$ integration time integrated over the spectrum and with all atmospheric species considered and no cloud cover.

We superimpose our results on top of Figure 3.3-7 from the HabEx report in Figure 7. Our integration times are based on a spectral integral (every wavelength considered). The HabEx report’s results are those calculated for the 0.2$\mu$m feature for O$_2$, and for the 0.2-0.3$\mu$m feature for O$_3$. We note that for O$_3$ we did not calculate integration times at the same discrete values used in the HabEx report as they used a fixed O$_3$ mixing ratio profile while we compute the profile photochemically based on the other species present in the atmosphere. We also summarize our O$_2$ integration times calculations in Table 4.
Table 4. Comparison of our HabEx (4 m) integration times with those of the HabEx report for a 5-σ detection of O$_2$ for an Earth-like planet orbiting at 1 AU around a Sun-like star at 5 pc. We explore ten different cases, each with an O$_2$ column mass of 100 g/cm$^2$ and 1 g/cm$^2$. 1) We use the code used to produce Figure 3.3-7 in the HabEx report and reproduce their results. N$_2$ is the only background gas. We report the integration times for 0.23 μm. These are the integration times reported in the HabEx report. 2) Same as (1) but for 0.76 μm. 3) We consider all of Earth’s background gases in our calculations. We report the integration times for 0.76 μm. 4) Same as (3) but the integration times are based on a spectral integral (every wavelength considered). 5) We set N$_2$ as the only background gas in our calculations. We report the integration times for 0.76 μm. 6) Same as (5) but the integration times are based on a spectral integral (every wavelength considered). 7) We consider all of Earth’s background gases in our calculations. We include tropical Earth-like clouds (Indonesia in November). We report the integration times for 0.76 μm. 8) Same as (5) but the integration times are based on a spectral integral (every wavelength considered). 9) We consider all of Earth’s background gases in our calculations. We include desertic Earth-like clouds (Algeria in July). We report the integration times for 0.76 μm. 10) Same as (9) but the integration times are based on a spectral integral (every wavelength considered).

| Case                                                                 | O$_2$ = 100 g/cm$^2$ (0.46 PAL) | O$_2$ = 1 g/cm$^2$ (4.6×10$^{-3}$ PAL) |
|---------------------------------------------------------------------|---------------------------------|---------------------------------------|
| 1. HabEx Report (N$_2$ + O$_2$) [@ 0.23 μm]                         | 1.6 hrs                         | 25.5 hrs                              |
| 2. HabEx Report (N$_2$ + O$_2$) [@ 0.76 μm]                         | 30.3 hrs                        | 2975 hrs                              |
| 3. Standard (All Species) [Integrated]                              | 16.6 hrs                        | 1299.0 hrs                            |
| 4. Standard (All Species) [@ 0.76 μm]                              | 28.9 hrs                        | 1662.8 hrs                            |
| 5. N$_2$ + O$_2$ [Integrated]                                       | 15.7 hrs                        | 1275.6hrs                             |
| 6. N$_2$ + O$_2$ [@ 0.76 μm]                                        | 28.5 hrs                        | 1647.0 hrs                            |
| 7. Standard (All Species) + Indonesian Clouds [Integrated]          | 36.5 hrs                        | 9915.4 hrs                            |
| 8. Standard (All Species) + Indonesian Clouds [@ 0.76 μm]           | 53.4 hrs                        | 12,374.3 hrs                          |
| 9. Standard (All Species) + Algerian Clouds [Integrated]            | 18.0 hrs                        | 1564.1 hrs                            |
| 10. Standard (All Species) + Algerian Clouds [@ 0.76 μm]            | 31.2 hrs                        | 2005.2 hrs                            |