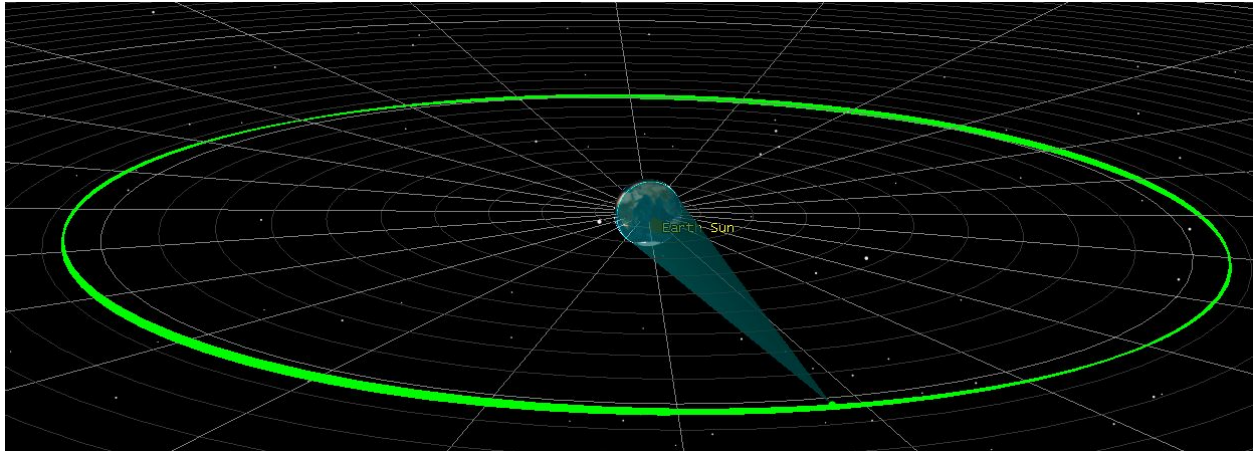


**Pale Blue Dot Explorer:  
A Case for Adding Earth to the Planetary Sciences List of Targets**



(STK-determined cis-lunar orbit for a Pale Blue Dot Explorer)

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## Abstract

Obtaining observational data to inform the science of future missions focused on Earth-like exoplanets is of prime importance for NASA Planetary Science and Astrobiology. However, Earth observations as a proxy for an exoplanet is an area of interdivisional research not well captured by existing NASA programs. To accommodate this, we propose adding Earth to the list of planets allowable by NASA Planetary Science Division's objectives and adding Earth observation to the cruise phase of planetary probes. A specific research investigation would be a spacecraft whose goal would be to characterize Earth as an exoplanet proxy — a Pale Blue Dot Explorer. Such a mission's objective would be to monitor the habitability and biological signatures of Earth in reflected light over broad wavelengths and phase angles.

## 1. Introduction

The area of Earth observation as a proxy for an exoplanet is an area of interdivisional research not well captured in NASA programs. This results in research centered around “Earth as an exoplanet” not fitting into any recent ROSES elements. Yet, obtaining data to inform the science of future NASA exoplanet missions is of prime importance. Given that Earth is the only known planet to host surface oceans and an active biosphere, assessing its remote signatures of habitability and biology should be an important priority for NASA given that Congress formally added Astrobiology as one of NASA's strategic objectives in 2017 [1].

Spectroscopic observations in reflected light yield critical information about the atmospheric and surface environment of a planet at any stage in its evolution. Only an Earth-focused mission (currently only allowed within NASA Earth Sciences) designed to understand characterization strategies for Earth as a guide to our search for life (a primary objective of NASA Planetary Sciences) on Earth-like exoplanets (a primary focus of NASA Astrophysics) can meaningfully respond to this important need. The time is now to obtain such a dataset because under-study NASA mission concepts have the goal to characterize Earth-like exoplanets in reflected light within the next two decades.

Indeed, NASA and its industry partners are investing heavily in building the next generation of space telescopes. Such telescopes will have the assessment of exoplanets for biological activity as one of their prime objectives. For example, one of the objectives of NASA's *James Webb Space Telescope* is to “determine the physical and chemical properties of planetary systems including our own, and investigate the potential for the origins of life in those systems [2]”. Yet, **the corresponding dataset for the actual Earth is an incomplete patchwork of measurements of varying quality**. No comprehensive dataset exists on our own planet's remote-sensing

signatures for habitability and biological activity (Section 3). Several missions have, as secondary objectives or for calibration tests, obtained snapshots of Earth [3], but the nature of the question “Are we alone in the universe?” warrants a new, primary dataset spanning a wide range of wavelengths and reflection (phase) angles. Such a generational dataset would be critical to feed current — and develop future — models to improve predictions of how habitable planets appear in reflected light. **The answer to this fundamental question is too important to rely on existing incomplete data.**

## 2. Earth as an Exoplanet is Not Captured in NASA Programs

NASA missions to observe Earth with a primary objective of assessing our planet for habitability and biological activity is *not* in the purview of NASA’s Earth Science program.

From the 2014 NASA Science Plan: “The purpose of NASA’s Earth science program is to advance our scientific understanding of Earth as a system and its response to natural and human-induced changes and to improve our ability to predict climate, weather, and natural hazards.”

Earth is excluded from the NASA Planetary Science Division purview, despite its goal to “[i]mprove our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere.”

From the 2014 NASA Science Plan: “The Planetary Science Division includes programs with three major classes of mission destinations: Inner Planets [...], outer planets [...], and small bodies [...].” The list for inner planets include Earth’s Moon, Mars and its satellites, Venus, and Mercury, but *not* Earth.

The focus of NASA Astrophysics in the search for life around *other* stars, precluding a mission to study the Earth as an exoplanet proxy.

From the 2014 NASA Science Plan: “NASA’s strategic objective in astrophysics is to discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.”

And yet, Earth as an exoplanet addresses multiple NASA and SMD research priorities. The 2010 Astronomy & Astrophysics NAS Decadal Survey states, “[o]ne of the fastest-growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable

zone — at a distance from their central star where water can exist in liquid form — and to characterize their atmospheres.”



**Fig 1:** Sequence of Earth and the Moon (faint source moving from lower-right of Earth to lower-left) from NASA’s *Galileo* mission. From Robinson and Reinhard (2020) [3].

### 3. Existing datasets

“Earth as an exoplanet” research would answer fundamental questions in exoplanet science: How do we validate numerical models of changing atmospheric signatures of an exo-Earth at multiple phase angles? How do we understand the myriad complex signatures of habitability and life in observations of Earth over a wide range of phase angles and wavelengths? No complete dataset currently exists to address these questions. The available published data are patchy and summarized in Table 1 (from Robinson and Reinhard, 2020 [3]) and are often acquired as secondary objectives or calibration tests.

Spacecraft	Observation Year	Phase angle(s)	Wavelength ( $\mu\text{m}$ )
<i>Galileo</i>	1990, 1992	35°, 82°, 89°	0.38 – 5.2
<i>MGS/TES</i>	1996	n/a	6 – 50
<i>EPOXI</i>	2008, 2009	58°, 75°, 77°, 87°, 86°	0.37 – 4.54
<i>LCROSS</i>	2009	23°, 129°, 75°	0.26 – 13.5
<i>DSCOVR</i>	ongoing	4° – 12°	0.318 – 0.780

For the dataset to be valuable for assessments of habitability, observation over a wavelength range from 0.2–5  $\mu\text{m}$  and phase angles from 0° – 180° would help answer four key questions:

**Question 1: Do temporally- and spectrally-resolved observations of the disk-integrated Earth unambiguously indicate that Earth is inhabited?** Is life unequivocally detectable on a planet? This question would be addressed by measuring the disk-integrated vegetation red edge signature and its rotational and seasonal variability. Required data would include moderate resolution ( $R \approx 50$ ) spectra spanning 650-800 nm, and one hour (or less) observational cadence over one year (or more). Additionally, measurement of atmospheric composition and its temporal variability would add value, and specifically concentration measurements of N<sub>2</sub>, O<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, O<sub>3</sub>, CH<sub>4</sub>, CO, N<sub>2</sub>O, SO<sub>2</sub>, NO<sub>2</sub>, NH<sub>3</sub>, OCS, HCN, C<sub>2</sub>H<sub>2</sub>, CFCs, acquired at (at least) four times over an Earth orbit would be beneficial.

**Question 2: Do phase-resolved, disk-integrated observations of Earth reveal a surface environment that can sustain liquid water?** This question would require measuring several planetary parameters. Surface pressure would be obtained by measuring the disc-integrated reflected light of Earth over a wavelength in the near-infrared to capture N<sub>2</sub>-N<sub>2</sub> dimer (4.3  $\mu$ m) and Rayleigh scattering (350–600 nm). Surface temperature would be measured (or deduced) from measurements of thermal emission (3.5–5.0  $\mu$ m) and atmospheric composition and surface pressure. Water vapor surface partial pressure could be obtained by measuring the disk-integrated flux across water vapor bands in the visible and near-infrared. And ocean glint contributions at all phase angles could be measured by low-resolution spectroscopy or photometry at visible through near-infrared wavelengths.

**Question 3: Do disk-integrated observations of Earth reveal a planetary surface environment that is suitable for the maintenance of Earth-like life?** This question would also benefit from knowing several planetary parameters. The planetary rotation rate could be determined by measuring (photometrically) the disc-integrated flux from Earth at (at least) one hour cadence. Aurora-driven emission features (that indicate a planetary magnetic field) for the disk-integrated Earth would require very high-resolution spectra in the visible wavelength range.

**Question 4: Do unresolved observations of the Earth-Moon system indicate the presence of a lunar companion to Earth?** This question would be best answered by measuring the lightcurves for the Earth-Moon system to detect eclipse and transit events, and measuring the phase-dependent thermal emissions variations from the Moon in unresolved spectra using moderate resolution ( $R \sim 50$ ) spectroscopy spanning 3–5  $\mu$ m.

#### 4. Recommendations

#### 4.1 Updating NASA's Planetary Science Division's Objectives

**We recommend a change in NASA's Planetary Science Division's objectives.** Specifically, Earth would be added to the list of inner planets permissible for study in the Planetary Science Division with the following clause: "Earth investigations with objectives solely relevant to the Earth Sciences division are not solicited in Planetary Sciences."

#### 4.2 Obtaining Measurements from Space-Based Platforms

Because the key questions above rely on disk-integrated measurements, two possible mission scenarios can plausibly obtain the needed data.

##### 4.2.1 Observations During "Cruise Phases" of Planetary Probes

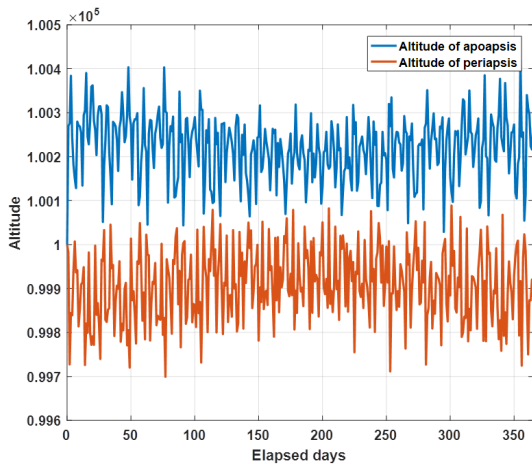
Cruise phases of planetary probes offer a unique opportunity for Earth observation. During sometimes multi-year interplanetary transits, the primary science objectives of such missions are on-hold and the spacecraft is dormant. Instead, these phases could provide a critical, synergistic opportunity through which to perform "Earth as an exoplanet" science.

##### 4.2.2 Observations from a Dedicated Mission: The Pale Blue Dot Explorer

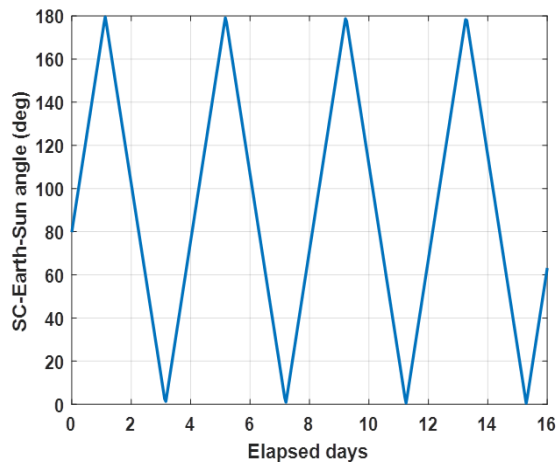
A specific research investigation within the area of interdivisional research discussed above would be a spacecraft whose goal would be to characterize the Earth as an exoplanet proxy - a Pale Blue Dot Explorer.

A Pale Blue Dot Explorer mission would further respond to the NAS Astrobiology Strategy recommendation "[t]o advance the search for life in the universe, NASA should accelerate the development and validation, in relevant environments, of mission-ready, life detection technologies." Furthermore, a Pale Blue Dot Explorer dataset would help assess how terrestrial biosignatures change from full phase to crescent sliver, responding to the NAS Astrobiology Strategy recommendation to "support expanding biosignature research to addressing gaps in understanding [...] the breadth of possible false positives and false negative signatures." The current collection of whole-disk datasets are incomplete, especially in the NIR (precluding the use of, for example, DSCOVR's ten narrowband channels which are in the range of 317–779 nm). A Pale Blue Dot Explorer would produce a complete dataset.

A preliminary mission concept study was undertaken to broadly assess what a Pale Blue Dot Explorer mission would entail. For this scenario, we assumed a spacecraft (s/c) mass of 100 kg with a surface area of 0.5 m<sup>2</sup>. We found that a cis-lunar orbit lying in the ecliptic plane at an altitude of 10<sup>5</sup> km would be stable and satisfy mission observation requirements with a conical sensor that has a half-angle of of ~3.5°. To compute orbit stability, the orbits were integrated numerically using AGI’s Systems Tool Kit (STK) with a high fidelity propagator that included the EGM08 Earth gravity field with 50x50 harmonics, third body effects from the Sun and the Moon, and a spherical solar radiation pressure model. The simulations were scripted to compute various initial configurations based on circular altitudes from 10<sup>3</sup> km to 10<sup>5</sup> km. These initial orbital elements were selected for arbitrary insertion, where the orbit does not need lunar-orbit resonance. Therefore, the analyzed orbits are stable in any possible configuration (Fig. 2). Critically, such an orbit at 10<sup>5</sup> km would allow observing the full parameter-space of phase angles in roughly 4 Earth days (Fig. 3), and be able to capture all latitudes < 87° (as opposed to <81° at GEO, 3.6·10<sup>4</sup> km, which would miss Antarctica). Electric propulsion would likely be required for orbit insertion from LEO.



**Fig. 2:** Orbital Stability of s/c at 10<sup>5</sup> km



**Fig. 3:** Phase-angle coverage of s/c

## 2. Conclusions

The area of Earth observation as a proxy for an exoplanet is an area of interdivisional research not well captured in NASA programs. And yet, Earth as an exoplanet addresses multiple NASA and SMD research priorities. Spectroscopic observations in reflected light yield critical information about the atmospheric and surface environment

of a planet at any stage in its evolution. "Earth as an exoplanet" research would answer fundamental questions in exoplanet science. Because NASA and its industry partners are investing heavily in building the next generation of space telescopes, and the existing datasets to represent Earth as an exoplanet are an incomplete patchwork of measurements of varying quality, **we recommend a change in NASA's Planetary Science Division's objectives to include Earth.** This would enable cruise phases of planetary probes to offer a unique opportunity for Earth observation. A specific research investigation would be a spacecraft whose goal would be to characterize the Earth as an exoplanet proxy - a Pale Blue Dot Explorer.

#### References:

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- [3] Robinson, T. D., & Reinhard, C. T. (2018). Earth as an Exoplanet. arXiv:[1804.04138](https://arxiv.org/abs/1804.04138).