National Aeronautics and Space Administration

FY25 Strategic University Research Partnership (SURP)

Next Generation Exoplanet Mission Simulations: Atmospheric Constraints

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Objectives: Add new capabilities to the exoplanet direct imaging tool, EXOSIMS, for yield studies of Earth-like worlds and ultimately inform architecture decisions for NASA's Habitable Worlds Observatory (HWO).

- Until now, EXOSIMS has evaluated observation success based on whether photometric data meets a predetermined signal-to-noise ratio (SNR) for specific spectral resolutions and wavelengths. These thresholds were set by separate, high-fidelity spectral retrieval studies, external to the simulation itself.
- To align more closely with HWO's scientific ambition — detecting potential biosignatures on Earth-sized planets in the habitable zones of nearby stars — a fast, moderate-fidelity spectral retrieval engine is being integrated directly into EXOSIMS. With this upgrade, observation success will mean the confident detection of molecular species, including potential biosignatures.
- This integration includes generating phase-dependent and wavelength-dependent reflectance spectra to calculate the minimum SNR threshold for detection of potential biosignatures.

Approach and Results (year 2 of 3):

1. Modify EXOSIMS to receive a real-Earth phase function (Fig. 2)
    1. Validate with end-to-end mission detections (Fig. 3)
    2. Vary the inner working angle (IWA) cut-off to observe more detections at higher phase angles (Fig. 4)
2. Determine the required SNR for an observation as a function of phase angle using rfast (U of AZ)
    1. Determine fractional dimming for an Earth twin due to O2 absorption with the rfast forward model (Fig. 5)
3. Generate Earth-like spectra as a function of phase angle and semi-major axis (sma) with the ExoRel (Fig. 1)
    1. Modify all SNR and albedos in EXOSIMS to be a function of wavelength, phase angle, and sma

Next year:

4. Simulate end-to-end missions to score oxygen detection:
    1. Use rfast molecule detection SNR criteria to set the observation integration time
    2. Use ExoREL cached spectra as the planet signal
    3. Molecule detection on the 'observed' spectra

Background: To date, yield simulators generally emphasize numbers of detected planets (potentially as a function of planet size and orbital distance) while the science of HWO is focused on atmospheric characterization.. Mission yield simulators must be brought into closer alignment with the characterization goals of HWO through incorporation of realistic planetary populations and associated atmospheric spectral observables.

Significance/Benefits to JPL and NASA: By updating EXOSIMS with exoplanet atmospheric spectra, we ensure it becomes the most realistic and comprehensive yield tool available that sets a standard for the field. These advancements enable more accurate, science-driven yield predictions for HWO and beyond, with JPL and NASA at the forefront of innovation in the ongoing search for potentially habitable worlds.

The reflectivity of an Earth-like planet varies with semi-major axis (insolation) and phase

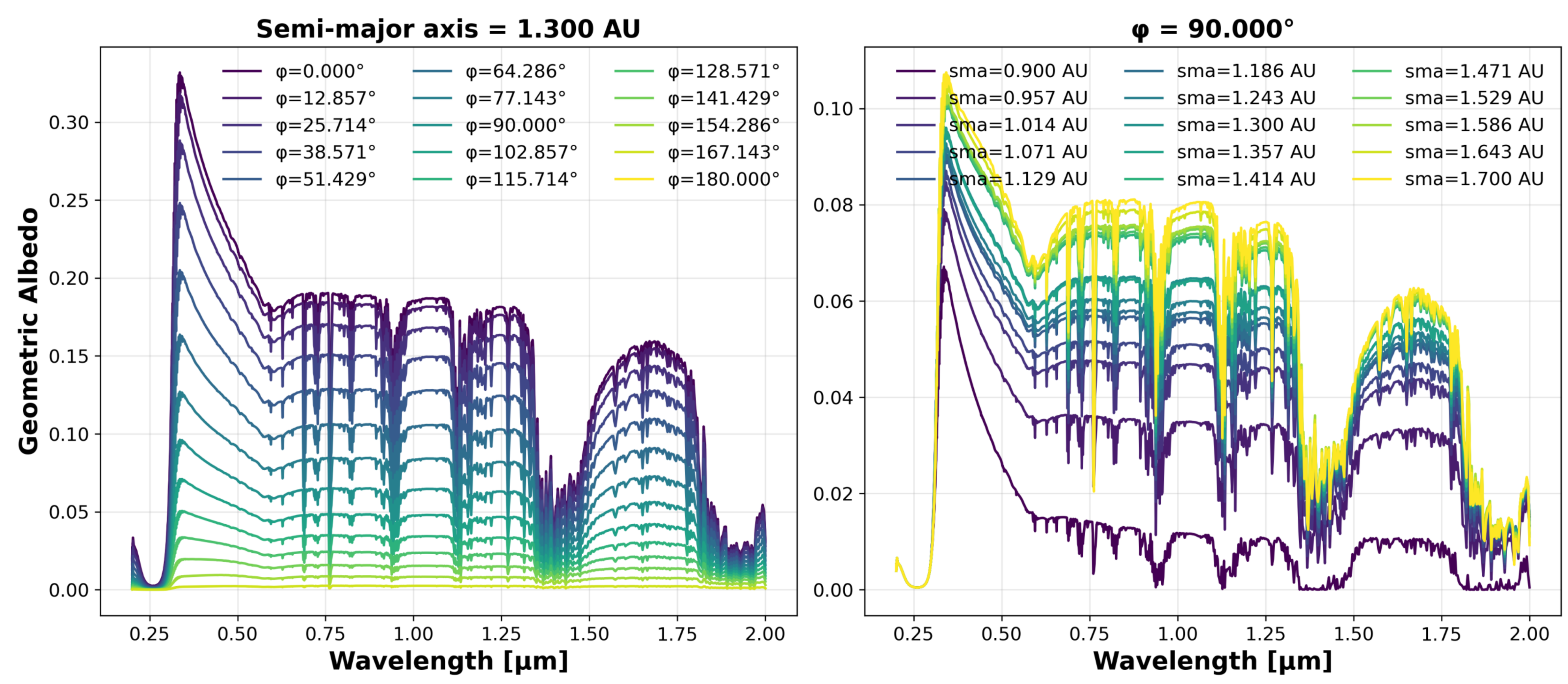

Fig. 1. *Modeled disk-integrated geometric albedo spectra (0.2–2.0 μm) generated with ExoReL for a Modern Earth-like planet around a Sun-like star.* **Left:** Semi-major axis fixed at **a = 1.300 AU**; phase angle **ϕ** varies from 0° (full phase) to 180° (full night side). Increasing ϕ lowers the apparent continuum level and reduces band depths. **Right:** Phase fixed at **ϕ = 90°** (quadrature); **a** varies from 0.90–1.70 AU. The increase in albedo with **a** is due to the formation and thickening of cloud layers in the atmosphere. Greenhouse effect is not included in these simulations.

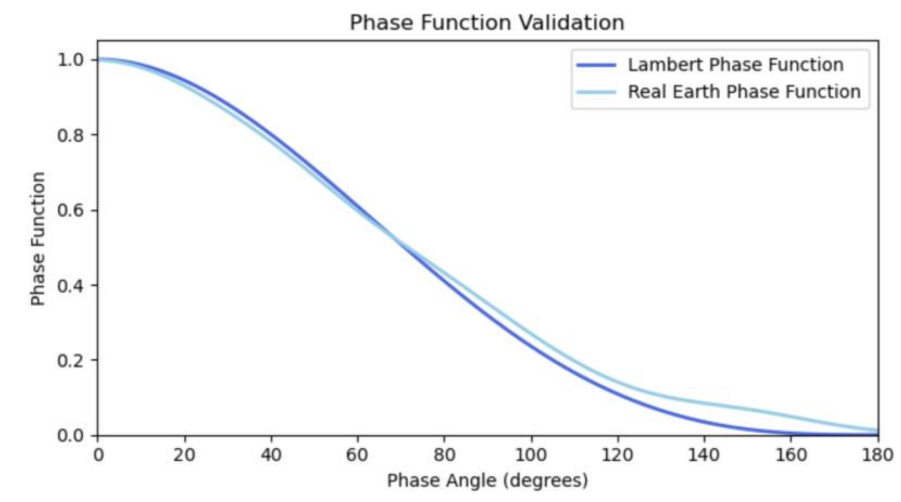

Fig. 2. Real-Earth and Lambert phase functions in EXOSIMS

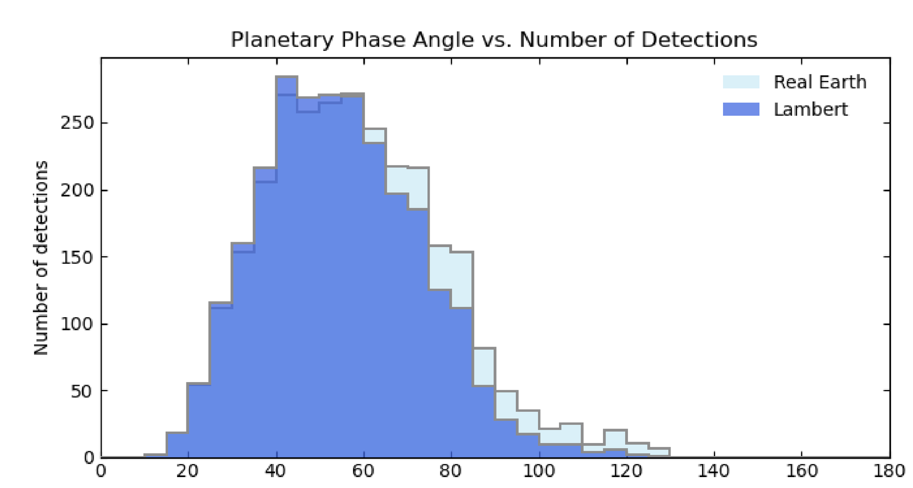

Fig. 3. Simulated detections increase where the Real Earth phase function is brighter

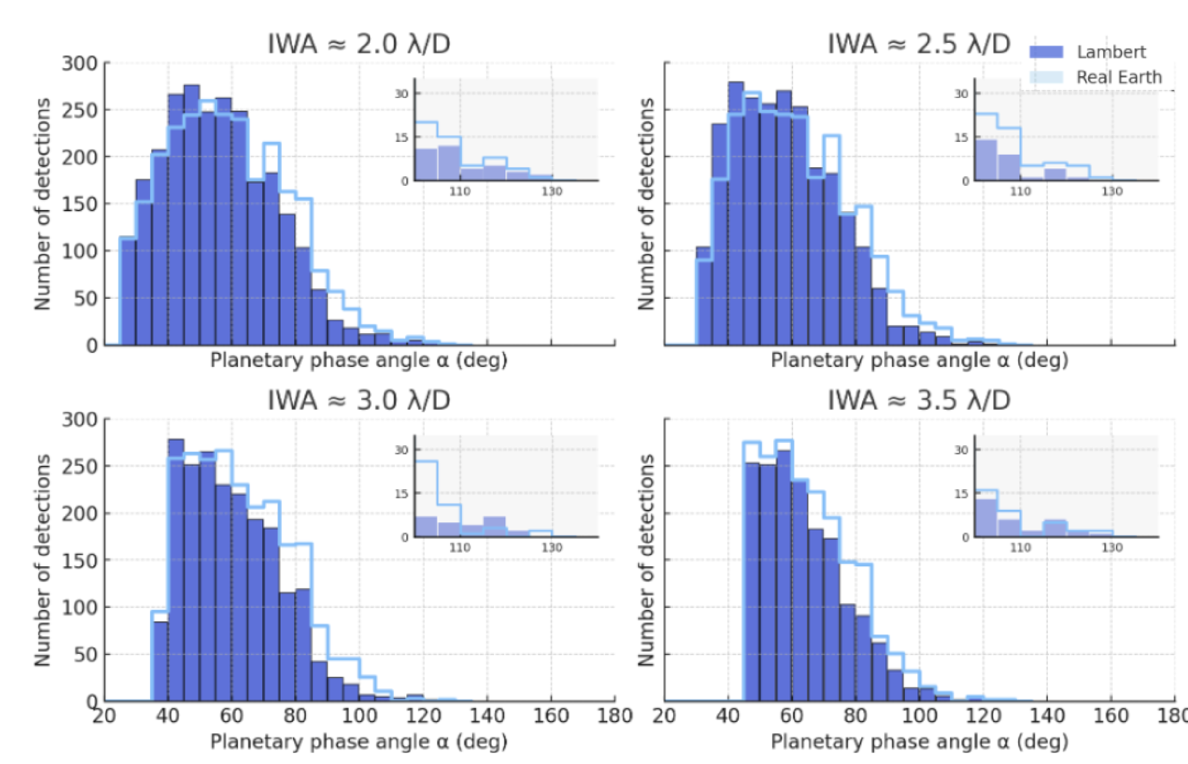

Fig. 4 (left). Validation testing showing that with varying IWA, the Real Earth phase function leads to increased detections for **ϕ > 70°**

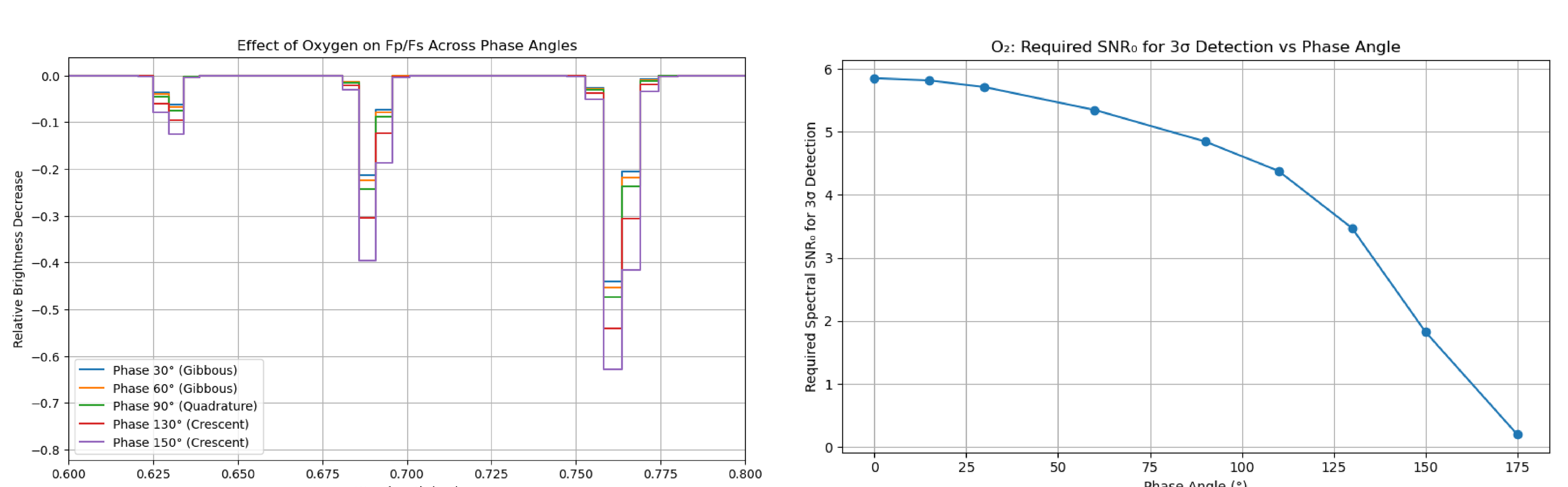

Fig. 5. left: Fractional dimming for an Earth twin due to O2 absorption, shown across phase angles, demonstrating that SNR can vary by a factor of 2 with phase angle. **Right**: Phase-dependent SNRs at 600 nm for a 3-sigma O2 detection.

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Publications: Searra Foote, Rhonda Morgan, Tyler D. Robinson, "Influences of a Realistic Earth Phase Function and Coronagraph Inner Working Angle on Yields for The Habitable Worlds Observatory" (in prep.)

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