

OPTIMIZED BROADBAND COLORS FOR DISCRIMINATING EARTH-LIKE EXOPLANETS. Angela M. Stickley¹, Noam Izenberg¹, Carey M. Lisse¹, Kathleen E. Mandt¹, Joseph J. Linden¹, Vikas Vepachedu¹. ¹Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA. (Kathleen.Mandt@jhuapl.edu).

Introduction: Distinguishing Earth-like worlds from the plethora of new exoplanet candidates is a key goal of the NASA Astrophysics program and preliminary attempts have been made using a variety of approaches [1-3]. One such approach was the 3-color photometric characterization of planets in the solar system using results from the Extrasolar Observation and Characterization (EPOCh) investigation on NASA's EPOXI mission, and found that the Earth occupies a unique space in three-color space [1]; **Fig. 1**.

Based on this result, and the similar work of Traub [2], we postulate that very simple, photon-efficient 3-color ratios be used to isolate Earth-like worlds in the growing inventory of exoplanets, allowing quick, accurate triaging and flagging of Earth-like worlds for deeper study by more expensive but more exact spectral discrimination experiments.

In an effort to prove this postulate, we conducted a study to design a simple, lower cost telescope/instrument to find "other Earths" assuming the capability to directly measure or derive a planet's reflectance spectrum. Although broadband filters are not seen to be precise diagnostics of planets with life, they can establish broad but critical similarity or difference to the one habitable planet we know.

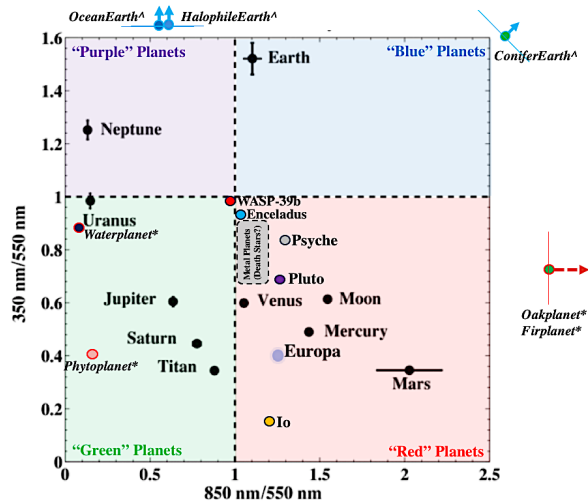


Fig. 1. Color-color plot from [1] updated to include Europa, Enceladus, Psyche, Pluto, and several hypothetical planets.

Methodology: We conducted an optimization exercise to arrive at three broadband filters that most reliably can separate modeled Earth-like, nominally habitable planets from other possible exoplanets. Criteria we used included:

- Atmosphere/clouds of habitable worlds
- Sea/Land proportions (ocean, granite, basalt, other surface material)
- Vegetation (chlorophyll spectra and fictional other photosynthetic materials depending on wavelengths of parent stars etc.)
- Other factors that can be spectrally modeled (planet-covering cities, world oceans, etc.)

We conducted a first-order optimization exercise with broadband filters based on [1,2], which was tweaked to separate Earth and Earth-like "habitable" words from others (*e.g.*, Mars-like, Venus-like, etc.), and using additional spectra and model spectra from the Virtual Planetary Laboratory (VPL) [4,5]. We intentionally limited our search wavelength range from 250 to 950 nm to plausibly enable a single-detector instrument.

Results and Conclusion: We have confirmed and extended the 3-color exoplanetary photometric discrimination work of [1] to other solar system bodies and some modeled planets as illustrated in **Fig. 3**. We found that the optimal filter combinations for diagnosing "Earths" is similar to [1] but slightly longer in UV and Visible wavelengths (Figs. 2 & 3). These optimized bands underscore the advantage of UV wavelengths and their potential utility for Earth-like exoplanet identification and/or discrimination in concert with other exoplanet observations. *The same filters are also useful for discriminating Ice giants like Neptune and Uranus due to their UV reflectance* (Fig. 3 top panel). Further implications of this study are that we established that Earth's unique optical colors are due to a combination of atmospheric oxygen/nitrogen with land masses.

Finally, we conducted a study of telescope size and integration time requirements to determine the feasibility of such an investigation. We found that strawman telescopes to search for Earths/Neptunes

out to 3/10 pc are not impractical. This means that an exoplanet survey that could quickly identify such planets could then be followed up by more detailed, longer term study by more intensive campaigns with more capable, but more resource or time constrained instruments.

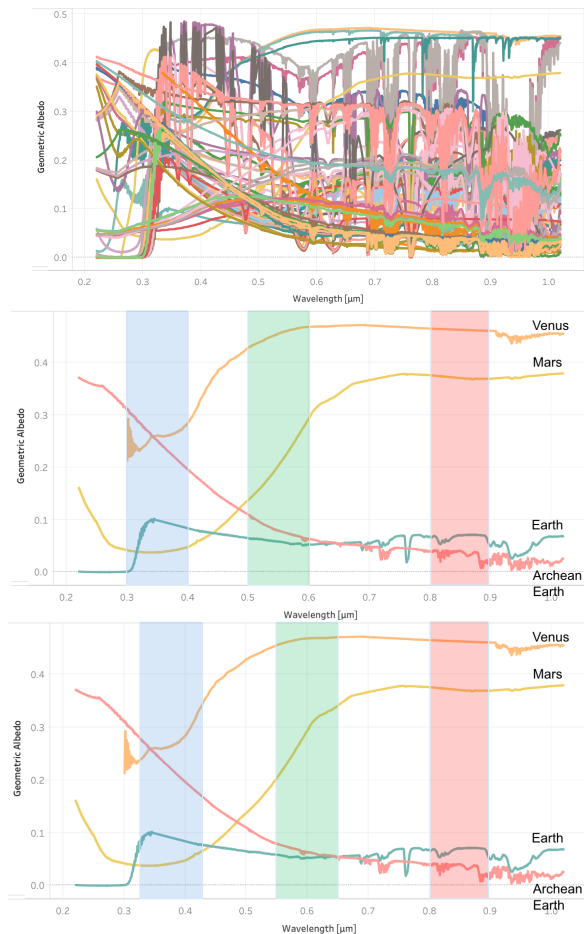


Fig. 2. Virtual Planetary Laboratory spectra analysis from the mid-ultraviolet through the near infrared. (top) 80+ Earth-like and near-Earth-like worlds [4,5]. Measured and modeled data of Mars, Venus, analogs, Archean Earths, thick, variable atmospheres, varying cloud types and cover, Earths around different stars, with different life covering the surface. (middle) Earth, Archean Earth, Mars, and Venus reflectance spectra overlaid with the filter set from [1]. (bottom) Terrestrial planet reflectance spectra overlaid by a more optimized filter set that increases separation of Earth-like planets by increasing both UV/Vis and NIR/Vis ratios of Earth.

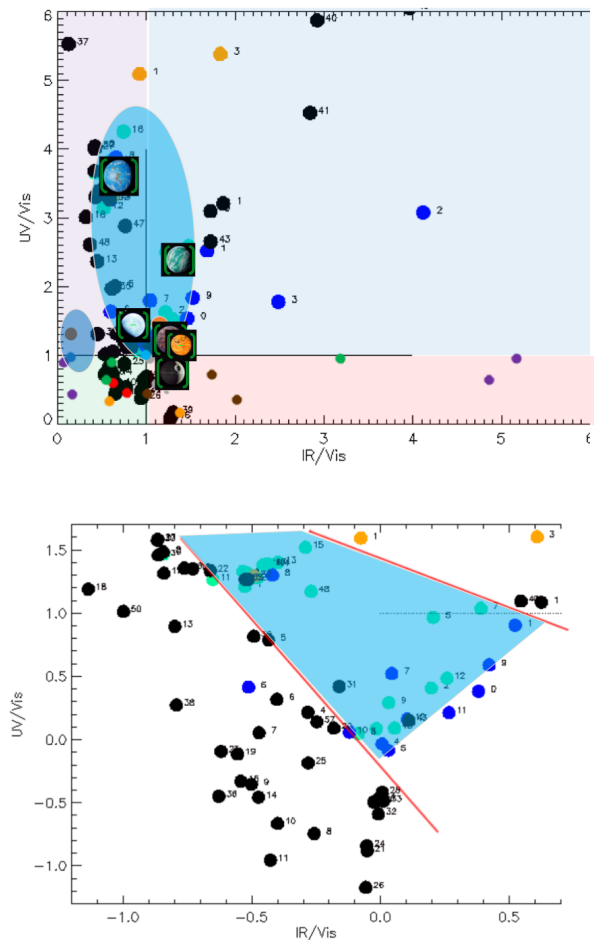


Fig. 3. Color-color plot using the VPL planets from the top panel of Fig. 2 and the optimized bands shown in the bottom panel of Fig. 2. Planets are categorized into Earth-like worlds (green), near Earth-like (blue), extreme atmospheres (orange), and non-habitable as we know it (black, red, brown and purple). (top) Large blue ellipse shows the zone of most Earth-like worlds in the data set. Small blue ellipse is zone of Ice giants Neptune and Uranus. (bottom) Same as top panel but presented in log-log space. The envelope of Earth-like worlds is somewhat cleaner.

References: [1] Crow+ 2011, *Astron. J.* **729**:130. [2] Traub 2003, *ESA SP-539*. [3] Krissansen-Totton *et al.* 2016, *Astron. J.* **817**:31. [4] Robinson+ 2011, *Astrobiology* **11**, 393 [5] Schwieterman+ 2016, *ApJ Lett* **819**, L13