Search for Exo-Earths in the Habitable Zones of Nearby Stars (SEEHZONS)

Jet Propulsion Laboratory
California Institute of Technology

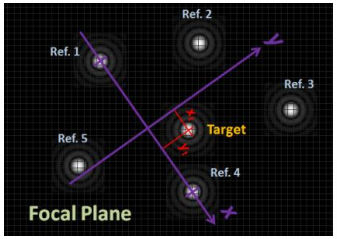
Overview:

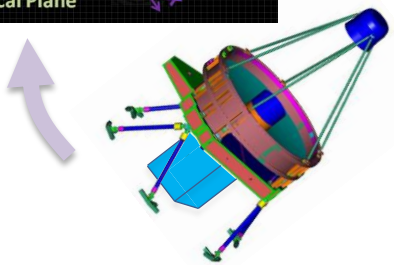
POC: Michael Shao (JPL) – Michael.shao@jpl.nasa.gov (818) 354-7834

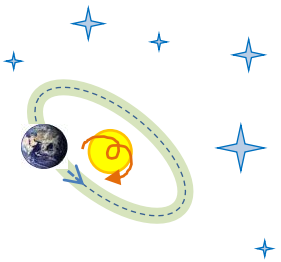
Key collaborators:
O. Guyon (Subaru), F. Malbet (Grenoble), B. Nemati(JPL), R. Goullourd (JPL).

The principle goal is to search over 150 nearby stars (over 3 years) for Earth clones in habitable zone orbits through ultra-precise astrometric measurements of the reflex motion of the star due to the orbiting planet. The nearest ~10 stars will be searched down to 0.5 Earth mass. Current estimates of η_{earth} (fraction of Sun-like stars with an Earth-like planet in the habitable zone) range between 3 and 30%; the nearest 5~50 Earth like planets should be found after a 3 yr mission. A 5 yr mission would give a proportionately larger yield. Secondary objectives include measuring the mass of Neutron stars and Black holes in binary systems, Ultra precise measurement of 10's of 1000's of Near Earth asteroid orbits, their size through stellar occultations and in many cases masses through near encounters.

Graphic:







Description:

The mission concept is a Discovery class mission that utilizes the 2nd NRO 2.4 m telescope.

The telescope would have a Nyquist sampled focal plane with 0.2 deg field of view and 32, 4K*4K arrays (CMOS or CCD) . It would have Laser metrology to measure the geometry of the pixels in the focal plane and a holographic element to calibrate the field distortion of the telescope optics. Using these features it will achieve 0.5 μas astrometry in 1 hr for most nearby bright stars.

The mission would have a duration of ~3 yr in a sun synchronous orbit, use a spacecraft bus similar to Kepler, and launched on a Falcon 9 vehicle.

The NRO telescope would be used unmodified, and two additional optics would relay the image, diffraction-limited over 0.2 deg FOV, to the focal plane.

The key technology is the metrology that would enable 0.5 μas astrometry. Our most recent results have demonstrated centroiding of an image to better than 9e-6 λ/D, corresponding to 0.5 μas when used with a 2.4 m telescope.

Value to NASA:

Exoplanets is one of NASA's major science themes.

This mission would be the next major advance in exoplanets, after Kepler and JWST's transit spectroscopy science program. The next major step is Earth clones (not super-Earths with hydrogen atmospheres) in habitable zone orbits around nearby stars.

Chief among the science areas impacted will be the discovery of all Earth clones that exist around nearby stars, but other important areas would be the masses of neutron stars and black holes, as well as investigation of dark matter .

Targeted μas-precision astrometry of objects across a wide range of brightness is unique to our concept, and its benefits extend beyond astrophysics to selection of targets for human exploration of near-earth asteroids and autonomous position knowledge and optical navigation in space.

PRE-DECISIONAL INFORMATION – For Planning and Discussion Purposes Only.
© 2012 California Institute of Technology. Government sponsorship acknowledged.

SEARCH FOR EXO-EARTHS IN HABITABLE ZONES OF NEARBY STARS (SEEHZONS)

Authors: Michael Shao (Point of Contact, JPL), michael.shao@jpl.nasa.gov;
O. Guyon (U. Arizona), F. Malbet (Grenoble), B. Nemati (JPL), R. Goullioud (JPL).

The authors have pioneered technologies in both exoplanet astrometry and coronagraphy.

Concept Summary: This white paper describes a barebones Discovery Class mission that can search over 150 nearby stars (over 3 years) for Earth clones in habitable zone orbits by making ultra-precise astrometric measurements of the reflex motion of the star due to the orbiting planet.

Primary Concept Goal Category: Astrophysics and Planetary Science, Human Spaceflight

SCIENCE INTRODUCTION

The first planet beyond our solar system was found in 1995, with the discovery of a "hot" Jupiter orbiting the star 51 Peg. Since then the field has blossomed with 800 confirmed exoplanets and over 2000 planet candidates from the Kepler mission, the vast majority of which are expected to be real. As instruments improved and new techniques for finding planets were invented, smaller and smaller planets were found, starting with Saturn mass then Neptune sized planets and finally Earth sized planets. The Holy Grail of exoplanet research has been an Earth clone: a planet not merely of Earth's size and mass but one that orbits in a sun-like star's "habitable zone" (HZ), where liquid water could exist on the surface. This Holy Grail has not been found.

The two prolific techniques, radial velocity (RV) and transits, have found the vast majority of exoplanets. But for Earth clones orbiting a nearby sun-like star, neither of these two techniques is likely to be successful. The most recent success of RV was the discovery of a planet whose mass ($M \cdot sin\, i$) was 1 $M_\oplus$ (Earth mass) in a 3-day orbit around Alp Cen B. Its RV signature was 0.6 m/s, much larger than an Earth-Sun (1yr orbit) whose signature would be a mere 0.09 m/s. A simple extrapolation of the α Cen B results show a survey of the 100 nearest G stars would take 200-400 years of observing time on a 4 m ground telescope. The transit technique, with the Kepler mission will search for Earth sized planets in 1yr orbits, but only for stars >500 parsec from the Sun, too far for confirmation with RV or astrometry or a future coronagraphic mission. Proposed transit missions TESS (NASA), PLATO (ESA), CHEOPS (ESA) are looking for super-Earth sized planet in short, ~month long orbits, excluding Earths in a 1yr orbit around a Sun like star.

EARTHS AND SUPER-EARTHS/MINI-NEPTUNES

As we find more and more exoplanets, their variety and abundance continue to amaze us. A current area of intense interest is super-Earths and mini-Neptunes. A planet with more than ~5 $M_\oplus$ has enough gravity to hold on to a Hydrogen atmosphere for billions of years. When it does have an H_2 atmosphere, it much more resembles Neptune (hence the label "mini-Neptune"), which is 80% hydrogen. Thus, a 5 $M_\oplus$ planet could be anything from a rock, with only a thin atmosphere like the Earth, to a planet where most of the mass is hydrogen. The only way to tell is to measure both the mass and the radius independently. Super-Earths/Mini-Neptunes are of intense interest at present because a number of future missions offer the possibility of measuring the spectra of their atmospheres: FINESSE (NASA), ECHO (ESA), and JWST (NASA).

The next major advance in exoplanets is the search for Earth clones in the habitable zone. Terrestrial planets like the Earth are a separate class. Hydrogen in the Earth's atmosphere will escape into space in a few hundred years. All of the inner planets of our solar system have roughly the same density, a much higher density than Neptune/Uranus. Quite likely a

PRE-DECISIONAL INFORMATION – For Planning and Discussion Purposes Only.
© 2012 California Institute of Technology. Government sponsorship acknowledged.

large fraction of super-Earths/mini-Neptunes have the same density as Neptune.

It would seem unlikely that an exoplanet with a hydrogen atmosphere could also have a significant amount of oxygen in its atmosphere, since with one lightning strike the oxygen and hydrogen would burn to produce water. Oxygen is the principle biomarker future TPF missions would look for. In the ultimate search for life outside of the solar system, we have to search for Earth analogs in the habitable zone, not super-Earths, or Earth mass objects in 2-day orbits.

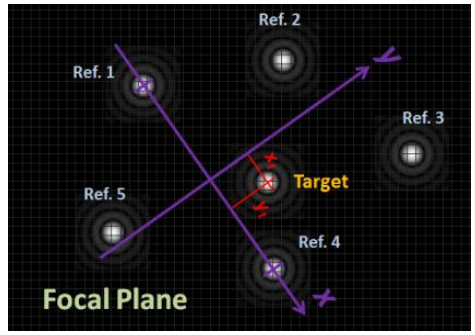
While 5 years ago any guess as to how many Earths in HZ orbits was as good as any other, the large, 3000-member list of exoplanets, especially those from Kepler, place much tighter constraints on η_{earth} (fraction of Sun-like stars with an Earth-like planet in the habitable zone). Two papers published in 2011 place lower and upper bounds of 3% and 30% on η_{earth}, respectively. If super-Earths are not considered, the bounds become 2~20%.

NRO-2 ASTROMETRIC MISSION CONCEPT

This concept paper describes an astrometric telescope capable of near photon-limited astrometry with a 2.4 m primary and a 0.2 deg field of view. The optical design uses the existing NRO-2 telescope primary/secondary, with just one additional curved surface to provide the correct plate scale for Nyquist sampling of the stellar images and to expand the diffraction limited FOV. We expect that the optics will be diffraction limited across the 0.2 deg field.

Astrometry with a staring telescope involves measuring the distance in the focal plane between a target star and a number of background "reference" stars, using the fact that distances in the focal plane map to angles on the sky.

The focal plane would be a collection of detectors with 6-10 μm pixels. A trade would be done between fewer, movable chips with finer sampling and the more traditional mosaic similar to Kepler. In the latter case, covering half of the 0.2 deg field with Nyquist-sampling pixels would require about 500 Mpix (e.g. 32 detectors, each with 4kx4k pixels).



We will be looking for Earth clones around nearby stars, and because they are nearby, these targets will be bright. The photon limit is due to the much fainter reference stars. The ~10 brightest reference stars in a 0.2 deg field on average will be ~13mag. The photon-limited astrometric precision in 1 hr would be 0.4 micro-arcseconds (μas).

Using the results of previous astrometric modeling and some basic scaling rules, we can arrive at a simple formula for how many stars will be accessible for search. The number of candidate host stars (N_s) grows as the distance to the 3rd power, while the required astrometric accuracy increases linearly with distance. The required integration time per star increases as the square of the needed accuracy. Putting it all together we have:

$$N_s \simeq 90 \cdot (\varepsilon/1\mu as)^{-1.2} \cdot (T_m/5yr)^{3/5}$$

where ε is the astrometric accuracy in 1 hr, and T_m is the mission lifetime. The factor 90 comes from a prior SIM mission study.

With the NRO-2, assuming an astrometric accuracy of 0.5 μas in 1 hr and a mission length of 3 yr dedicated to this one program, a total of ~150 nearby stars could be searched with enough sensitivity to find planets down to 1 $M_\oplus$ planet in orbits as long as 1 yr (scaled to stellar luminosity). Using 3~30% as the lower and upper bound for η_{earth}, we would expect to

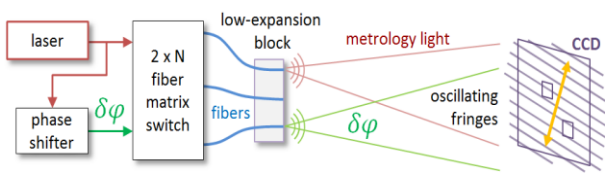
PRE-DECISIONAL INFORMATION – For Planning and Discussion Purposes Only.
© 2012 California Institute of Technology. Government sponsorship acknowledged.

find between 4 and 45 Earth clones. A 5-yr mission would search about 210 stars and find between 6 and 60 Earth Clones.

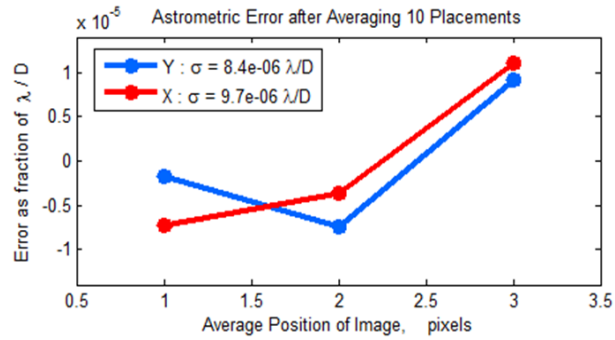
Beyond the photon limit, two sources of instrumental/systematic error are the focal plane and the field distortion of the optics. Field distortion calibration is described more detail by a separate white paper submitted by co-author O. Guyon.

The mosaic of detectors will, at the few micro-pixel (μpix) level, not be stable even for an hour. Even within one CCD, 10 μpix across 4000 pixels implies a stability of 2 parts per billion, and the CCD geometry is not expected to be stable at that level over years. Last of all, the QE is not uniform within a pixel, and all of these imperfections calibrated or if totally random, averaged out to a few μpix.

Our focal plane calibration approach uses heterodyne laser metrology, which places moving laser fringes on the pixels. The fringes are produced by pairs of fibers alternately lit to create different spatial frequencies in different directions. These metrology fringes let us calibrate the position of every pixel as well as the QE variations within every pixel.



In a recent lab demonstration of this approach, we illuminated a CCD detector that was calibrated in the above manner with a pair of artificial "stars." The detector was moved, in 30 steps, over a length equivalent to 3 pixels. The astrometric error was inferred from the variation in the measured inter-star distance as the detector was moved. Each distance measurement was itself an average of 10 placements. This averaging is traceable to on-orbit operation. The figure below shows the mean-removed inter-star distances in both dimensions. The standard deviation of the placement-averaged astrometric error was found to be about 9e-6 λ/D, translating to 0.4 μas when applied to the NRO-2 telescope. This first result indicates we are already within the ballpark of needed accuracy.



We are just starting experimental validation of the use of diffractive gratings to calibrate the optical distortion of a telescope. This activity is underway synergistically at the University of Arizona (Guyon) and JPL (Shao, et al.).

MISSION DESCRIPTION

A full mission study would have to be conducted to optimize the mission. The proposed science however could be achieved in a 3-year mission in a Sun-synchronous Earth orbit. Using a spacecraft similar to the one used by Kepler, the full flight system mass would be around 2,000 kg (1200 kg Telescope and barrel, 200 kg Instrument and 600 kg Spacecraft). A Falcon 9 launch vehicle would place the flight system in a 1,000 km-high sun-synchronous terminator orbit with plenty of mass margin.

Although the proposed mission would produce sub micro-arcsecond astrometry, the required pointing stability is very modest. The brightness of the targets and reference stars (visual magnitude > 13) means we will be reading the CCD's at > 10 Hz and the spacecraft attitude only needs to be stable to ~20 mas for 1/10 sec. Kepler has achieved ~3 mas pointing over 10's of hours. The expected data volume from a single target stars and less than a dozen reference stars is very small compared to the data produced by Kepler on 100,000 stars.

PRE-DECISIONAL INFORMATION – For Planning and Discussion Purposes Only.
© 2012 California Institute of Technology. Government sponsorship acknowledged.