Astro2020 Science White Paper

Finding Exo-Earths with Precision Space Astrometry

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Abstract (optional):

The next decade may provide us with an answer to the enigmatic question "Are we alone?" – the question that inspired generations of humans since the dawn of our civilization. The answer may come via unambiguous detection of biogenic gases and molecules in the atmosphere of an Earth's twin around a Sun-like star. However, before this we need to find such an Earth-like exoplanet.

We argue that astrometry may be the only technique that is capable of finding Earth-twins. Astrometry is a technique that measures the reflex motion of a star in the plane of the sky allowing one to determine a planet's mass and its orbital inclination. Astrometric measurements with precision at the level of ~1 μas enable surveys of a few dozens of nearby FGK stars thus allowing to search for a 1 $M_\oplus$ planet in the middle of the habitable zone (HZ); they also are capable of providing direct measurements of planetary masses and system architectures.

By determining the times, angular separation, and position angle at passages of periastron and apastron, precise astrometric measurements will allow the prediction of where and when a planet will be at its brightest. If astrometry is used contemporaneously with a coronagraph, it will greatly help in the search. This information (a) will be critical in the optimization of direct imaging observations and (b) may allow to eliminate model degeneracies in predictions of the planetary phase function in terms of orbit geometry, companion mass, system age, orbital phase, cloud cover, scattering mechanisms, and degree of polarization.

As ~15% of solar-like stars could have an Earth-like planet in or near their HZs, the 1-μas astrometric census of habitable exoplanets will be crucial for future exobiology missions. Thus, the exoplanets found with astrometric missions could become targets for follow-up missions for direct imaging and spectroscopy, thus enabling detection of the signs of life on an Earth 2.0.

1 Major objective for 2020-2030: Finding an Earth twin

Ever since the discovery of the first Jupiter-mass companion to a solar-type star, tremendous progress has been made in the field of searching and studying the exoplanets. Our knowledge about the processes and conditions for forming exoplanets is quickly expanding with thousands of newly discovered exoplanets. The skillful combination of high-sensitivity programs have unveiled a variety of planetary systems that exist in the Milky Way Galaxy. Preliminary estimates are now available for the occurrence rate of terrestrial-type planets in the habitable zone (HZ) of stars similar to our Sun (~10%) and low-mass M dwarfs (~50%). This progress positions us very close to the most intriguing questions concerning the birth of our civilization here on Earth.

However, despite major progress in finding exoplanets, we are still searching for those that may harbor conditions similar to that on our own planet. This is especially true when considering the possibility of an unambiguous detection of biogenic gases and molecules in the atmosphere of an Earth's twin orbiting a Sun-like star. What is most exciting is that we may to be able to answer these questions in the next 10-15 years. However, prior to spectroscopic studies of exo-atmospheres, we first need to find the most suitable candidates. Thus, finding Earth 2.0 should be the core of the exoplanetary search efforts in the coming decade.

Investigations of Earth-like planets, those with masses of 0.8-2 $M_\oplus$, orbiting their parent stars at the distances where liquid water could persist, would allow addressing the age-old questions related to the uniqueness of the Earth as a habitat for complex biology. This is an unprecedented, cross-technique, interdisciplinary endeavor. Finding biosignatures (via remote spectroscopy of O_2, O_3, H_2O, CO_2, and CH_4 gases) on planets where life similar to ours would have emerged and modified the atmosphere, would have a major impact on us. However, despite multiple ongoing efforts, the question of finding Earth analogues is still unanswered.

2 Astrometry is well suited to find an Earth 2.0

We argue that precision astrometry from space may be the key technique to allow for discoveries mentioned above. With recent advances in astrometric detector calibration techniques (Zhai et al., 2011, Crouzier et al 2016), newly-developed flight metrology techniques (Shao et al, 2011), availability of the highly-precise astrometric catalogues (e.g., Gaia 2018), and existence of various mission concepts (Malbet, 2016, Shao et al, 2018), it is time to consider optical astrometry as a primary technique for a space mission aiming at the discovery of Earth-like exoplanets.

There are several techniques that are capable of finding exoplanets, the most frequently used are radial velocity (RV), and planetary transits. Even though these two techniques have succeeded in finding thousands of exoplanets (with most them being Neptune or super-Earth sized planets), the ultimate goal of finding an Earth's twin in a 1AU orbit around a solar-type star remains unfulfilled.

Astrometry is the only technique that can find Earth-mass planets in HZ orbits around ~99.5% of nearby FGK stars. Currently, transit missions have found the largest number of new exo-planets. However, for solar-like stars, a planet in the HZ only has a 0.5% probability of transiting. For a transit mission to detect an Earth-line exoplanet around a Sun-like G star, the mission must observe many transits to build the SNR for detecting a $1R_\oplus$ planet transiting a G star.

An original goal of the Kepler mission was to detect an Earth 2.0 around Sun-like G stars. The transit of an such a planet in front of the Sun causes the solar flux to dim by 10^{-4}. Due to a combination of a slightly increased instrumental noise and stellar photometric variability, Kepler needed ~8 yrs to see 8 transits to build up the SNR for detecting a $1R_\oplus$ planet transiting a G star. However, with failure of 2 out of 4 reaction wheels in ~4 yrs after launch, this goal was abandoned. Multiple transit missions were approved after Kepler, e.g. *TESS*, *CHEOPS*, *PLATO*. However, none of them will have an 8-yr mission lifetime, necessary to detect 1 $R_\oplus$ planets in a 1 yr orbit. In addition, the same star field must be observed, which is not the design for *TESS* or *CHEOPS*.

Missions relying on planetary transits are all aimed at short-period planets. $TESS$, and future $PLATO$ mission will make tremendous progress for Earth-sized planets around M stars. However, these planets will be tidally locked to the host star and, thus, are quite different from our Earth. While even a tidally locked exo-Earth is extremely interesting, it is a qualitatively different type of planet compared to our Earth. If the Earth were orbiting an M star, it would likely be tidally-locked, so that the water would evaporate from its sunlit side and would condense as ice on the dark side. While our Earth is ¾ covered with water, that water is only a few km deep. On a tidally-locked Earth, the dark side would have a thick (few km) layer of ice, a very large Antarctica. In fact, once water gets on the dark side on such a planet, it stays on that side, drastically reducing chances of life. Thus, it is hard to imagine that life could exist on any tidally-locked planet.

As the probability of finding an exo-Earth in our stellar neighborhood is rather small, it would be more practical to conduct the search and the follow-up campaigns separately, but contemporarily. If this is done by a single large coronagraph, one would have to increase the search volume by a factor of a few hundred, which is impractical. Also, ideally, after finding such a planet (for instance, using astrometry for this purpose), one needs to immediately follow-up the discovery with a reasonably sized coronagraph.

Although, the RV and transit techniques have succeeded in finding thousands of exoplanets, these efforts will not allow us to find an Earth's twin in a 1AU orbit around a solar-like star. Currently, the best accuracy achieved by RV technique is ~40 cm/s. An Earth-Sun system would have a RV signal of 9 cm/s. Multiple ultra-high precise instruments are under construction with the goal of achieving the accuracy of 1 cm/s. However, the astrophysical noise due to stellar activity such as radial pulsations could affect RV at ~30 cm/s, complicating the detection. In addition, the RV method can only determine the product $M^*\sin(i)$, but not the planet's mass nor its orbital inclination i. The $\sin(i)$ ambiguity is important when looking at exoplanets in the regime between large rocky planets and mini-Neptunes. This inclination ambiguity is the primary reason why 95% of exo-Earths may be missed by RV and transit methods; the price we cannot afford.

Planets with masses $> 5\ M_\oplus$ can hold on to a hydrogen atmosphere for a billion years, but the planet with such a hydrogen atmosphere is really a mini-Neptune. Planets that can support life like our Earth and perhaps like an ancient Mars, have relatively thin atmospheres over a rocky solid surface. We emphasize the importance of measuring masses in exoplanet detection. Kepler and RV have discovered a large number of exo-Neptunes and super-Earths. Neptunes and larger planets are gaseous planets mostly made of hydrogen. Rocky planets in the solar system (Earth's density is 5.5 g/cm^3) have a density much higher than gaseous planets (Neptune's density is ~1.6 g/cm^3). If a rocky exoplanet (similar to our Earth and smaller planets) would also have liquid water on its surface, it may also support life similar to that on the Earth. Thus, it is important to measure the mass of the planet without the $\sin(i)$ ambiguity (although arguments exist favoring rocky super-Earths ($1\ M_\oplus < M < 5\ M_\oplus$) as life-hosting worlds). Astrometry could provide such measurements.

2.1 Astrometry is the most suitable tool to find Earth 2.0

Precision astrometry measures the reflex motion of the star in 2D, from which both the planet mass and orbit inclination can be derived. As opposed to other methods, such as Doppler spectroscopy, astrometry is less sensitive to the disturbances (causing only astrometric bias at 0.08 μas level) due to stellar activity (i.e., spots, meso-structures) (Lagrange et al. 2011). Astrometric detection of an exo-Earth at SNR=6 would result in a 1σ error on the planet mass of ~$0.25\ M_\oplus$. As such, astrometry is a unique tool for discover exo-Earths. In addition to finding exo-Earths, astrometry may be used to determine their masses and orbits, which is an added benefit of this technique.

To detect an exoplanet, position of the parent star must be observed many times, so that the reflex motion due to an orbiting exo-Earth will be reliably detected. To detect the reflex motion at low

SNR, the observational period must be longer than the period of the planet. Our numerous numerical simulations have shown that using a periodogram to detect an orbit requires a signal-to-noise ratio (SNR) of SNR~6, so that the false alarm rate would be small < 1%. We define SNR is as the amplitude of the periodic reflex motion of a star divided by $error/sqrt(N)$, where $error$ is the 1 hr astrometric error and N is the total number of hours observed during the mission.

While both RV and transit techniques are good at finding planets with very short orbits (on the order of days), astrometric measurement of stellar reflex motion of exoplanets, on the other hand, is more sensitive to longer orbits. However, astrometry has a more robust sensitivity exactly where RV detectability starts to decline. RVs may detect a couple of low mass, rocky planets in the HZ, but 95% of those will be missed and astrometry locks in that critical parameter space. For a terrestrial planet in the HZ of nearby G stars, a typical signal level is 0.3 μas (i.e., Earth at 1 AU of a Sun, at 10 pc), an angular size equivalent to a coin thickness on the Moon as measured from the Earth. The possibility of an Earth transit is ~0.47%, making hard to detect. In fact, neither of these two methods (RV or transit) is optimized for finding planetary systems like our own, as the possibility of an Earth transit in a 1-year orbit around a *G* star is very small only ~0.47%. Such challenges motivate to search for better tools needed to find Earth 2.0. Astrometry is the most valuable among other techniques for this purpose.

A concept like *LUVOIR* is so large that it would detect exo-Earths both astrometrically and via direct detection. However, the diameter of a coronagraphic telescope is linearly related to the distance of that Earth 2.0. Knowing where the nearest half-dozens of exo-Earths are, lets one design a coronagraphic mission that can get spectra of those known exo-Earths. The cost of a space telescope goes as ~$D^{2.7}$, so knowing where the targets are can significantly reduce the uncertainty in the cost of the coronagraphic mission. With detector metrology designed and demonstrated at JPL, the ~9-15-m aperture *LUVOIR* could do both direct detection of Earth 2.0 as well astrometric detection. Thus, an astrometric detection of a planet around the nearest ~100 stars would only take ~100 hrs of integration time on *LUVOIR*. An astrometric precursor mission is needed to make these large space-based facilities to be most efficient with the targets known prior to their launch.

Once a planet if found, the next task is to detect the light from it and measure its spectra. Coronographic instruments on the next generation space telescopes (such as the concept studies for HabEx, LUVOIR, OST) will obtain atmospheric spectra. The simulations for these mission studies show that independent detection will make these missions more efficient, saving precious time on the 10-m class space telescope for characterization. In fact, is it more economical to use astrometry to "discover" exo-Earth and then use larger facilities for characterization.

We emphasize that, if astrometry is used contemporarily with the coronagraph, it helps in the search. By determining the times, angular separation and position angle at periastron and apastron passage, astrometric position measurements will allow the prediction of where and when a planet will be at its brightest, thus (a) crucially helping in the optimization of direct imaging observations and (b) relaxing important model degeneracies in predictions of the planetary phase function in terms of orbit geometry, companion mass, system age, orbital phase, cloud cover, scattering mechanisms, degree of polarization (Madhusudhan & Burrows 2012).

The detection or the non-detection of Earth-mass planets can guide the observations of future large direction detection missions. In a direct detection of the light from exo-Earths, whose angular separation is only slightly larger than the IWA (inner working angle of a coronagraph/starshade), a single observation has only a small chance of detecting the planet when it spends most of the time inside the IWA. Even after a single detection, we will not know the orbital semi-major axis and whether the planet is Neptune-sized at 4 AU or Earth-sized at 1 AU. And if at two epochs a faint dot is detected, one will not know whether the two dots are in fact the same planet or two different planets. Astrometric non-detection with a lower limit of $1M_\oplus$ means a future mission can avoid spending ~86% of its time on stars that do not have an exo-Earth and concentrate on the 15% that do, with repeated direct observations even the first few tries could have the Earth 2.0 inside the IWA and not be detected.

How many stars one has to search before finding ~10 exo-Earth? While the Earth's mass and its radius are well defined quantities, the definition of the HZ is less clear. Event our own Earth would not have liquid water if it were in the Venus's or Mars' orbits. Since the fraction of stars in the HZ depends on the "width" of the zone, there is still a debate on the definition of HZ. Is there a value for astrometry mission "preceding" a coronagraphic mission? We argue that there is.

There are immense challenges ahead (photospheric velocities) for detecting smaller signals with RV, even with instrumental precisions of 0.1 m/s (*ESPRESSO* and *EXPRES* have demonstrated this). If we do not invest in astrometry now, we risk taking a back seat to some of the greatest discoveries that will be made by astronomers in other countries in the next decade. Furthermore, the inclination restriction for transits and RV measurements means that the vast number of small planets will be invisible to these methods. Unlike the RV and transit methods, *astrometry*, even if used alone, can measure reliably and precisely the true mass and 3-dimensional orbital geometry of an exoplanetary system. These parameters are fundamental inputs to models of planetary evolution, biosignature identification, and habitability.

2.2 *Number of Targets vs Astrometric Accuracy*

The presence of a Sun-Earth system at a distance of 10 pc could be seen via a sinusoidal astrometric signal with an amplitude of 0.3 μas and a period of one year. To reduce the false alarm probability to the level of lower than 1%, normally one has to make a number of measurements over a period of at least 1 year with a cumulative precision that is 6 times better than the sinusoidal amplitude. We need at least a SNR=6. If one makes 144 measurements over 2-3 years, each measurement should have a 1-σ precision of at least 0.6 μas. For stars whose luminosity is different from the Sun, we assume that Earth 2.0 will be at a distance where the parent star's flux on the surface of the planet is the same as on our Earth. For the nearest star(s), the Alp Cen binary system, the astrometric signature is 3.4 μas for Alpha Cen A and 2.4 μas for Alp Cen B. Earth 2.0 would be ~10 times easier to detect around Alpha Cen A than at an Earth-Sun twin at 10 pc. Our search would of course start with the easiest target (Alpha Cen) progressing to more distant stars. As we choose targets more distant than Alpha Cen, we will spend more observing time on the target to be able to detect Earth 2.0.

Table 1. Sensitivities of various methods a function of distance & telescope diameter.

Parameters	Time vs Distance	Time vs Diameter	Comments
Astrometry	R^2	$1/D^4$	
Radial Velocity	R^2	$1/D^2$	
Direct detection	R^2	$1/D^2$	starshade

2.3 *Scaling factors*

It is useful to consider the effect on total observing time when the target is more distant for various sizes of the telescope. Table *1* shows the increase in integration time needed when the telescope size is changed or the target distance change to maintain SNR>6 needed to detect Earth 2.0. The table assumes that systematic errors can be controlled at the level of photon noise.

The astrometric signal decreases as $1/r$, while the star's brightness decreases as $1/r^2$. However, the photon noise in astrometric measurements is not the photon noise from the nearby target star (7 mag) but from the reference stars (~11-13 mag), whose brightness does not depend on the distance to the target star.

Table 2. Number of exo-Earths discovered with astrometry as a function of telescope's diameter.

Telescope diameter, m	Observing time, years	Number of exo-Earths
0.35	3	11
0.5	3	25
0.7	3	57
1.0	3	134
1.4	3	292

The number of stars that can be searched for a 1 $M_\oplus$ planet is an effective 1 AU orbit depends on the amount of observing time allocated as well as the size of the telescope. In Table 2, we make the assumption that for small telescopes < 1.5 m that a total of

2.6×10^4 hours (i.e., 3 yrs) were available in a dedicated astrometry mission. For larger telescopes we assume 10% of the time of a 5-year mission (i.e., 0.5 years of astrometry) was available or we calculate the amount of observing time needed to search the nearest ~400 FGK stars.

The observing time only includes integration on the target not the telescope slew time. Table 3 shows that with large general-purpose telescopes, the observing time needed to search the nearest ~400 FGK stars represents a small fraction of the available time for a major space observatory. An astrometric camera with the appropriate laser metrology calibration could be one of several instruments on a large >2 m class space telescope. This wide field imaging camera would have other astronomical uses besides astrometry.

Table 3. Number of exo-Earths discovered with astrometry as a function of the telescope diameter.

Telescope diameter, m	Observing time	Number of exo-Earths
2.0	10% of 5 yrs	244
3.0	2,000 hrs	400
6.0	124 hrs	400

3 Technologies needed for micro-arcsecond astrometry

Traditionally systematic errors have been the major challenge μas-level astrometry from space. Astrometric accuracy has a lot in common with photometric accuracy, and the technology development that proceeded the Kepler mission demonstrated ~ 10^{-5} relative photometry. Similar advances have been made in detector calibration for astrometry. Photons from stars carry the astrometric information at exquisite precision, systematic errors are imparted when those photons strike the telescope optics and also when they are detected by the focal plane array.

The calibration of optical field distortion using reference stars is a technique that is perhaps a century old and used on ground and space-based telescopes. For exoplanet detection, the value of the distortion need not be calibrated to μas-level of accuracy. If the distortion is constant, it does not need to be calibrated at all. For large telescope that also have an exoplanet coronagraph, the stability of the optics at the single digit picometer level exceeds the stability requirements for micro-arcsecond astrometry. Thus, given a perfectly stable telescope, the LUVOIR high-definition imaging camera would greatly benefit from the metrology for the focal plane array. Thus, a space astrometry mission prior to *LUVOIR* would allow to retire technology risks and to demonstrate the capabilities that will increase the efficiency of a 5-year *LUVOIR* mission.

Focal plane errors arise because of two related sources of error. An ideal pixel has QE=1 inside the pixel and 0 outside the boundaries of the pixel, and the pixels are uniformly space at the level of ~10^{-4}-10^{-5} pixels. In reality pixel boundaries are not sharp step functions, and they are uniformly space only at the ~ 1% of pixel level for most backside silicon focal planes. In addition, the QE within the pixel is uniform again only at the ~ 1% level. A 1m telescope with 0.1 arcsec FWHM images centroiding to 1 μas implies we know where the pixels are to 10^{-5} pixels. The graphic at the beginning shows lab results where the relative separation of two diffraction limited images were measured with 10^{-5} λ/D precision while the pair of images were moved across a CCD.

For telescopes that do not have hyper contrast coronagraph level stability requirements, there are some alternatives. One is the diffractive pupil concept that puts a precision array of dots on the primary, which produces a regular pattern of dots in the focal plane. One way to use the diffractive pupil is to look at a very bright star (0 mag) and record the diffraction pattern interspersed with observations of a much dimer target star (~7 mag). The diffractive pupil can also be used during science observations. But when the target star is ~7 mag photon noise of the diffracted light can be significantly higher than the photon noise of the reference stars (~11-14 mag).

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