Search for Terrestrial Planets with SIM Planet Quest
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ABSTRACT

SIM is an astrometric mission that will be capable of 1 microarcsec relative astrometric accuracy in a single measurement of ~1000 sec. The search for terrestrial planets in the habitable zone around nearby stars is one of the main science goals of the project. In 2001, NASA through the peer review process selected 10 key projects, two of which had as its goal, the search for terrestrial planets around nearby stars. The two teams, one led by G. Marcy (UC Berkeley) and one lead by M. Shao (JPL), have an extensive preparatory science program underway. This paper describes the status of this activity as well as the technology status of SIM’s narrow angle astrometry capability, to reach 1 uas in a single epoch measure and its ability to average multiple epoch measurements to well below 1 uas.

Keywords: Exoplanets, terrestrial planets, astrometry, interferometry

1. INTRODUCTION

The Space Interferometry Mission (SIM) is a 9 meter baseline Michelson stellar interferometer, designed to make precise astrometric measurements of the position and motion of astrophysical objects. SIM consists of 3 interferometers with roughly parallel baselines. Two of the interferometers will look at bright ~7 mag guide stars. The third interferometer will move among a number of science targets.

SIM has two different observational modes, global or wide angle astrometry and narrow field astrometry. In global astrometry, stars over SIM’s 15 deg field of regard are observed in what we refer to as a “tile”. SIM is then moved to point to an adjacent interlocking “tile”. Adjacent tiles share a number of stars. After the whole sky is observed with interlocking tiles, a global least squares solution is performed to derive the positions of the objects in a global
coordinated frame. That frame is locked to inertial space through 25–50 QSO’s that are among the many thousands of objects SIM will observe. The goal for SIM is 4 uas accuracy.

In narrow angle astrometry, SIM will observe a target star, with respect to 3–6 nearby (within 1 deg radius) reference stars. The goal is 1 uas accuracy in the position of the target and 1 uas accuracy in the reference stars in less than 30 minutes of observation for stars within a 1 deg radius field brighter than 10 mag.

The SIM project has a series of technology milestones, the first four were necessary for the project to transition from phase A to phase B, the last four are necessary for the project prior to entering phase C. As of July 2005, all eight technology milestones have been completed. In addition several engineering milestones involving the construction and testing of picometer metrology components (under simulated launch vibration and thermo-vac conditions) have been completed.

This paper briefly describes how SIM makes narrow angle measurements, how they are used to find planets, and the prospects for finding terrestrial planets with SIM.

2. NARROW ANGLE ASTROMETRY

Global astrometry involves measuring the position of target objects with respect to the Grid. Within a tile, there will be on the average ~7 grid stars spread over the 15 deg circular field of regard. The time between an observation of a target star and a grid star is typically ~30 minutes. SIM has two types of instrumental errors, one called time dependent error which is caused by small and slow thermal drift of the optics, and the second one called field dependent errors which are errors or biases that are the result of moving the optics to observe stars in different parts of the sky.

Narrow angle astrometry is a mode of operation where both of these errors are made much smaller than in global astrometry. The raw numbers for SIM 1 uas narrow angle astrometry and 4 uas global astrometry are a bit misleading. The global astrometry accuracy of 4 uas is the accuracy of a series of measurements over the 5 year mission lifetime of SIM. The Grid stars will have their positions measured to 4 uas. The proper motion of the stars will be accurate to < 3 uas/years and the parallaxes will be accurate to ~4.6 uas. The 4 uas position applies to the position of the star at the middle of the mission, 2.5 years into the science program. The grid is observed 22 times over 5 years, with each star being observed ~220 times. Because of the overlapping tiles each star is observed several times when the grid is measured. The required accuracy of a single measurement in wide angle mode is ~12 uas, in order for the mission accuracy to be 4 uas.

Narrow angle accuracy refers to the accuracy of a single measurement, which at 1 uas, is slightly more than an order of magnitude more accurate. The reason global accuracy is quoted for the mission is because prior global catalogs also quoted mission accuracy. The hippocras mission quotes ~0.7 mas accuracy. Narrow angle astrometry will be used primarily to find dark companions to stars, and in planet search programs, single measurement accuracy is most often quoted.

SIM achieves instrumental accuracy in narrow angle astrometry, that is an order of magnitude better than in global astrometry by limiting the field of view to 1–2 deg and by chopping. Thermal drift of the instrument over ½ hr in global astrometry measurements are reduced to 90 sec chopping period. The SIM narrow angle observation scenario is show in the figure on the next page.
Typically, SIM will spend 30 sec integrating on a star and 15 sec to slew between stars.

This observing sequence is the one that was tested in the laboratory at JPL as part of the technology milestones mentioned previously. The SIM narrow angle error budget is roughly evenly divided into instrumental and photon noise, (0.7 uas for photon noise and 0.7 for instrument). The instrument error in turn is divided into the science interferometer (0.5 uas), the guide interferometers (0.35 uas), and the external metrology truss (0.3 uas). The guide interferometers are constantly looking at the guide stars, so their error is simply the thermal drift of a science interferometer that isn't moved on purpose. The science interferometer's error allocation is then ~0.5 uas or ~24 picometers. Milestone 6 was passed when we demonstrated that the accuracy of the science interferometer was better than 24 picometer more than 68% of the time.

3. SEARCHING FOR TERRESTRIAL PLANETS

Corrections from Differential Measurements to Local Frame

The route from a single epoch measurement to finding a planet is moderately complex. First the reference stars are not stationary objects at infinity. In general they will be K giant stars 10 mag at a distance of 500~1000 parsec. Even if these stars are single stars, they will have proper motion of ~ 1000 uas/yr and a parallax effect of ~ 1000 uas. Because of the parallax of the reference stars, our sensitivity to planetary periods of exactly 1 year will be compromised. The parallax of the reference stars will be determined by measuring their positions with respect to grid stars, with and accuracy of ~4 uas. Planetary periods of exactly 1 year will be undetectable unless their amplitude is greater than ~4 uas. The range of planetary periods that are compromised is inversely proportional to the SIM mission length. A 5 year data set will have a 20% range of periods around 1 year while a 10 year data set will have a 10% range of periods around 1 year where the planet search sensitivity will be reduced by a factor of ~4.

The target star will also have proper motion, and parallax. Because the targets are nearby stars, their proper motion will be large, typically 0.1 arcsec/yr and their parallax signatures will be equally large 0.1 arcsec for a star at a distance of 10pc. The last major astrophysical effect is differential stellar aberration. The absolute stellar aberration effect caused the velocity of the spacecraft orbiting the Sun, is quite large. Since SIM will be in essentially a 1 AU orbit, its aberration will be similar, +/-20 arcsec over a year. For differential measurements over a 1 deg field of view, the differential aberration is smaller by a factor of sine (1 deg) or +/- 0.35 arcsec. Aberration will be corrected by navigational information obtained from ground based microwave tracking of the spacecraft. The size of the effect 0.35 arcsec must be predicted to slightly better than 0.5 parts per million. This in turn means the 30km/s velocity of the spacecraft around the Sun must be measured to better than 1.5cm/s.

After correcting for the motion of the reference stars, and differential stellar aberration, we’re left with the motion of the target star in the “local” frame. This reference frame is not inertial, it has an unknown proper motion and unknown absolute parallax. However these limitations don’t affect the search for a periodic motion of the star caused by an orbiting planet.
Finding Evidence of Periodic Motion

The most common technique used to find periodicity in data is the periodogram. This approach has long been used in radial velocity searches for planets. The main difference for SIM is that astrometry measures two coordinates of motion. The periodogram, unlike the FFT, doesn’t require that the data be taken at regular intervals. In fact, non-uniform temporal sampling is key to avoiding aliasing.

Planets are known to exist with orbital periods ranging from 3 days to 300 years. SIM with a 10 year mission goal can not expect to be able to efficiently detect planets with orbital periods much longer than 10 years. Still, if we have uniform time sampling of the position of a target star, the Nyquist theorem says we need to measure the position of the star at twice the highest frequency, or we need to measure the star’s position every 1.5 days. Over a 5 year period, this means 1200 measurements. A periodogram with non-uniform time sampling can uniquely identify an orbit with far fewer measurements (about a factor of 10~15 fewer in the case of SIM’s planet program).

The simplest method for combining the data in both x and y measurements is to add their periodograms. There is a relation between the periodogram power and the probability that a planet exists, in addition, it’s straightforward to calculate the probability of a “false alarm”.

After the existence of a periodic signal in the position of the target star is found, we fit a keplarian orbit to the motion. SIM is much more sensitive to planets than pervious techniques and it’s likely that not only will SIM find smaller planets but more multiple planet systems. The technique for finding the second planet is to subtract the keplarian orbit of the largest planet from the star’s motion and process the data with the periodogram to find evidence of a second planet.

What Astrometry Tells Us

Astrometric detection of a planet gives us all (6) orbital parameters of the orbit and the mass of the planet. It should provide these orbital parameters for all the planets in that stellar system (whose astrometric signature is > 1 uas). One of the prime reasons for the SIM mission is to look for Terrestrial planets in the habitable zone of other stars. The habitable zone is the orbital radius where the starlight is approximately the same as the intensity of Sunlight on the Earth, where the temperature on the surface of the planet is consistent with the existence of liquid water. The orbital radius tells us if the planet is in the habitable zone. The eccentricity of the planet, tells us what the seasonal variation of the surface temperature will be. The mass of the planet will tell us the surface gravity (all rocky planets have roughly the same density). The planet’s gravity is the key to holding onto an atmosphere. Very small planets like Mars have a very thin atmosphere. Planets 20 times the size of the Earth, like Neptune and Uranus, are mostly atmosphere. The largest planets like Jupiter are composed mostly of hydrogen.

For planetary systems with multiple planets, the orbits of the planets can be used to ascertain the long term stability of the orbits. In a double star system, the gravitation perturbation of the stars precludes a large range of orbital parameters for stable orbits. In our solar system, Jupiter plays a significant role in determining what orbits are stable over billions of years.

The SIM Search for Terrestrial Planets

The search for planets around nearby stars starts with a list of candidate stars. The solar neighborhood, within 30 parsec is well known. We initially narrowed the list of candidate stars to stars brighter than 10 mag. We then eliminated any giant stars, restricting ourselves to long lived main sequence stars. The search for terrestrial planets ultimately is about the possibility of finding life outside our solar system. Our search is centered on planets in the habitable zone. These are planets whose distance from the parent stars will result in a surface temperature similar to the Earth. We then eliminated stars whose planets in the habitable zone would have orbital periods greater than 10 years. The reason is that astrometry detects the wobble of the planet around the star, and given a mission goal of a 10-year life, orbital periods longer than 10 years will be significantly more difficult to detect than shorter orbital periods.
Of the ~3000 stars within 30 parsec of the Earth, the above selection reduces the list to ~1400 stars. We then conducted monte carlo simulations of SIM observations of hypothetical planets around these stars to determine the probability of detecting a planet around that star. With ~17% of the SIM mission devoted to the terrestrial planet search, there is only time to search ~250 of these stars with sensitivity to detect a 1 uas astrometric perturbation. The monte carlo simulations were designed to let us pick the most promising candidates.

**Reasons Why Some Stars are Better Candidates than Others.**

Astrometry is more sensitive to stars 2 parsec away than 20 parsec. If there was a planet orbiting Alp Centuri in its habitable zone, SIM could detect it if its mass was larger than 0.4 Earth masses. But a similar star at 13 parsec, SIM’s minimum detectable mass would be 4 Earth masses.

A star 4 times as luminous as the Sun would have its habitable zone at 2 AU as oppose to 1AU for our Sun. A planet in a 2 AU orbit would have a larger astrometric signature, making it easier to detect.

More luminous stars are in general also more massive. A more massive star would not wobble as much as a lighter star. However the mass and luminosity of main sequence stars are not independent, Luminosity ~ mass^3.8. Stars that are slightly more massive are much more luminous. As a result it’s easier for SIM to detect planets in the habitable zone around massive stars than low mass stars. This is true until the orbital period of the planet becomes longer than 10 years.

SIM’s accuracy is limited by two broad noise sources. Instrumental errors and photon noise from the target star and photon noise from the reference star. Photon noise is roughly 50% of the total SIM narrow angle error budget. All else being equal SIM will be more accurate looking at a 7 mag star than a 10 mag star. While we have placed a 10 mag cut on the starlist, the vast majority of the 250 stars in the final list are brighter than 7 mag.

Photon noise is important not just for the target star, but also the reference star. The availability of reference stars within a 1 deg radius is set by nature; the stars are where they are. Some target stars have a large selection of possible reference stars, 20 or more potential reference stars, a few targets do now have enough (min of 3) reference stars to conduct a narrow angle astrometric campaign. Furthermore bright reference stars are better than dim reference stars, because their photon noise will be smaller.

Reference star geometric placement is important. This needs some background information. The fringe position of a star is given by \( FP = \text{baseline} \times \cos(\theta) \), where the baseline is nominally 9m and \( \theta \) is the angle between the baseline vector and a vector to the star. For a star nominally perpendicular to the baseline the fringe position is \( \text{baseline} \times \sin(\phi) \) where \( \phi \) is the angle between the star an a vector normal to the baseline. SIM, and all astrometric instruments, have field dependent biases. One way to look at these biases is that the effective baseline length changes slightly depending where in the 15*15 deg field the target is. This change in effective baseline length is unimportant at the 4 uas level for wide angle astrometry but is a dominant error, if uncorrected, for 1 uas narrow angle astrometry.

The correction is performed by using 3 or more reference stars. A minimum of 3 reference stars can be used to solve for the “plate scale” or baseline length. Ideally the target star is at the center of 3 or more symmetrically placed reference stars. We have defined a term called the reference star geometry photon noise error multiplier. For reference stars that are symmetrically placed about the target star the noise multiplier is 1.0. For highly asymmetrically placed reference stars the noise multiplier is > 1 reducing our relative astrometric accuracy. For most target stars we have an excess number of reference stars. For example if we have 9 potential reference stars we can program a computer to calculate the geometric noise multiplier for all possible combinations of 3-4 reference stars out of the 9 candidates. Our reference stars are all brighter than 10 mag and there exist catalogs that are almost complete down to 11 mag (e.g., the Tycho 2 catalog). We then know all the reference stars available for all ~1400 potential candidate stars. We then calculate the geometric noise multiplier for all possible combinations of reference stars around all 1400 potential candidate target stars.
Optimizing Observing Time

If the target star were 10 mag and the reference stars were all 10 mag, we get the highest astrometric accuracy by spending one half our time integrating on the target star and one half our time integrating on our 3~5 reference stars. But most of our target stars are < 7 mag while reference stars are between 7 and 10 mag. A differential astrometry measurement between the target and ensemble of reference stars has photon noise from both the target star and the reference stars. The optimal observing scenario would collect roughly equal number of photons from the target star and reference stars. But since the target stars are ~10 times brighter than the reference stars we would spend most of our time integrating on the fainter reference stars.

All of these issues mentioned here affect the minimum detectable planet mass. The stars on the list were then ranked in order in terms of minimum detectable planet mass in mid-habitable zone. The “best” 250 stars are then tabulated below. The nearest stars are the two components of the alpha centauri wide binary system. The furthest star on the list is ~25 parsec distant.

<table>
<thead>
<tr>
<th>Minimum Mass Planet Detected</th>
<th>Number of Stars Searched by SIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 Me</td>
<td>5 stars</td>
</tr>
<tr>
<td>&lt; 2</td>
<td>12</td>
</tr>
<tr>
<td>&lt; 3</td>
<td>45</td>
</tr>
<tr>
<td>&lt; 4</td>
<td>110</td>
</tr>
<tr>
<td>&lt; 5.3</td>
<td>250</td>
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</table>

Conclusion

The SIM Planet Quest project has refined its terrestrial planet search strategy in a number of ways, which includes optimizing the observing strategy to picking the best targets with the best reference stars to observe. Between now and launch, it’s reasonable to expect some further minor improvement in our ability to find terrestrial planets. Overall the program is quite robust, able to find terrestrial planets down to 0.4 Earth mass around alp Cen and below 5.3 Earth mass around 250 nearby stars.

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