Looking for Earth-like Planets with the SIM Planet Quest Light Mission

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Abstract—The Space Interferometry Mission Planet Quest Light (SIM PQL) is a new concept for a space borne astrometric instrument. It will be located in a solar Earth-trailing orbit. SIM PQL utilized technology developed for the Space Interferometry Mission Planet Quest (SIM PQ). The instrument consists of two Michelson stellar interferometers and a telescope. The first interferometer chops between the target star and a set of reference stars. The second interferometer monitors the attitude of the instrument in the direction of the target star. The telescope monitors the attitude of the instrument in the other two directions.

SIM PQL will be capable of one micro-arc-second narrow angle astrometry, over a two-degree field of regard for magnitude 6 and brighter target stars. During the 5-year mission, SIM PQL would search 50 nearby stars for planets of mass down to one Earth mass, in the Habitable Zone, which have orbit periods of less than 3 years. SIM PQL will also perform global astrometry on a variety of astrophysics objects, reaching 6 micro-arc-seconds absolute position and parallax measurements. As a pointed instrument, SIM PQ will maintain its astrometric accuracy on fainter objects.

This paper will describe the instrument, how it will do its astrometric measurements and the expected performance based on the current technology.

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1. INTRODUCTION

The Space Interferometry Mission PlanetQuest (SIM PQ) is a space borne instrument [1], capable of astrometric measurements to micro-arcsecond precision on the visible light from a large sample of stars in our galaxy and search for earth-like planets around nearby stars [2]. SIM PQ will carry out a 5 year mission from an Earth-Trailing Solar Orbit. SIM is a key project of NASA's Navigator program and Search for Earthlike planets and life. The SIM PQ instrument is an optical interferometer system with a baseline of 9 meters, and includes two "guide" interferometers for spacecraft pointing reference and a "science" interferometer to perform high accuracy astrometric measurements on target stars.

The Planet Quest Light (PQL) is a cost effective alternative concept for SIM PQ. With a smaller 6 meter baseline and a 30 cm telescope instead of a third interferometer, PQL will still achieve many of SIM PQ's original science objectives. The overall cost of PQL, close to half of the SIM PQ cost to complete, makes PQL an attractive candidate for flying an astrometric mission by 2015.

Figure 1 shows the discovery space for planets with PQL. Estimated GAIA performance is for a search of ~50,000 stars fainter than V = 7 at a median distance of 50 parsecs.

[1] 1-4244-1488-1/08/$25.00 ©2008 IEEE.
[2] IEEEAC paper #1374, Version 2, Updated October 30, 2007.

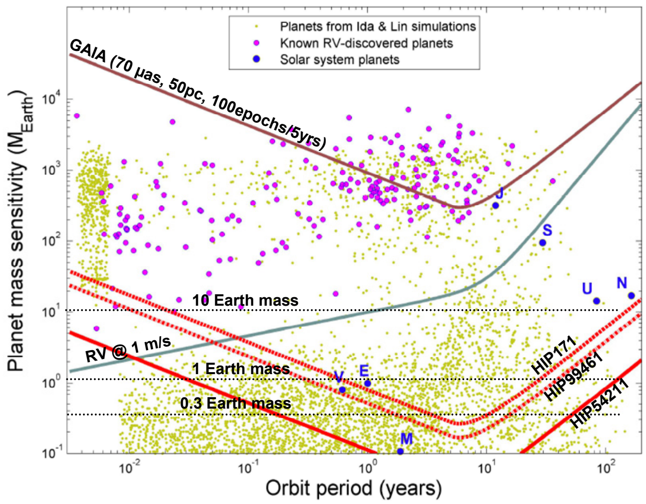

Figure 1 – The HZ of sun-like stars with planets in the 0.3 M_{Earth} to 10 M_{Earth} range. In a 5 yr mission, PQL achieves 1Me/HZ searches around 65 stars. For all of those stars, PQL will find planets of lower mass further from the star and planets of greater mass both closer and further from the star, characterizing the full planetary system of each of the 65 stars searched.

SIM has successfully addressed many technological challenges in order to show the mission was technically achievable. These challenges range from nanometer-level control problems to picometer-level sensing problems [3]. Key testbeds and brass-board components have been designed, built, and tested during the technology development phase of SIM, resolving all the major technology challenges. Examples of such demonstrations include the System Test-Bed 3 [4], the Micro-Arcsecond Metrology testbed [5], the Kite testbed [6] and the Thermal-Opto-Mechanical testbed [7]. The results from these series of testbeds form the evidence that the technological challenges faced by SIM are achievable. This technology developed for SIM directly applies to the Planet Quest Light mission.

2. INSTRUMENT

Astrometry with an interferometer

The basic elements of a stellar interferometer are shown in Figure 2. Light from a distant source is collected at two points and combined using a beam splitter, where interference of the combined wavefronts produces fringes when the internal pathlength difference (or delay) compensates exactly for the external delay. Thus, the angle between the interferometer baseline and the star can be found using the measured internal optical path difference (OPD), according to the relation:

$$\cos\alpha = \frac{\vec{B}\cdot\hat{s}}{B} = \frac{x}{B} \tag{1}$$

where x is the relative delay (OPD) of the wavefront to one side of the interferometer due to the angle. Thus, the astrometric angle α between the interferometer baseline and the ray from the star can be measured if the length of the baseline B and the internal delay are measured. In a stellar interferometer, the external metrology system measures the distance between two fiducials (each made of common-vertex corner cubes) and the internal metrology measures the optical path difference to the beam combiner from the two fiducials. Finally the starlight fringe detector measures the total optical path difference all the way to the star.

Planet Quest Light (like SIM Planet Quest) is a Michelson interferometer operating in the visible spectrum. Light from a star is collected by two 30 cm telescopes separated by a 6 meter baseline. From the two collecting telescopes, the light is propagated by a set of optics to the beam combiner where the two optical wavefronts are re-combined, forming interference fringes. The peak interference fringe is obtained when the propagation path through the two arms of the instrument is identical. The internal metrology sensor measures the internal propagation difference between the two arms (also known as internal delay), from the fiducials on the collecting optics all the way to the re-combining optic, to the single picometer accuracy[3]. When the instrument is tracking the peak interference fringe, the external delay is the complement of the internal delay. Therefore, the measurement of the internal delay is an excellent estimation of the external propagation delay. Simultaneously, the external metrology sensor determines the length of the baseline, defined by the two fiducials, to similar picometer-level accuracy. Figure 2 shows that the ratio of the external delay to the baseline length is the cosine of the angle between the baseline and the star.

[3] The precision metrology systems used on PQL measure length changes only. Thus, when each interferometer locks on its target, it is only keeping track of the changes in the angle between the star and the baseline: the overall delay and hence the overall angle is not measured. Similarly, it is not the baseline vector that is measured by the external metrology system, but the changes in the baseline vector. The PQL approach is to perform a fit to the data after a large enough group of grid stars have been observed.

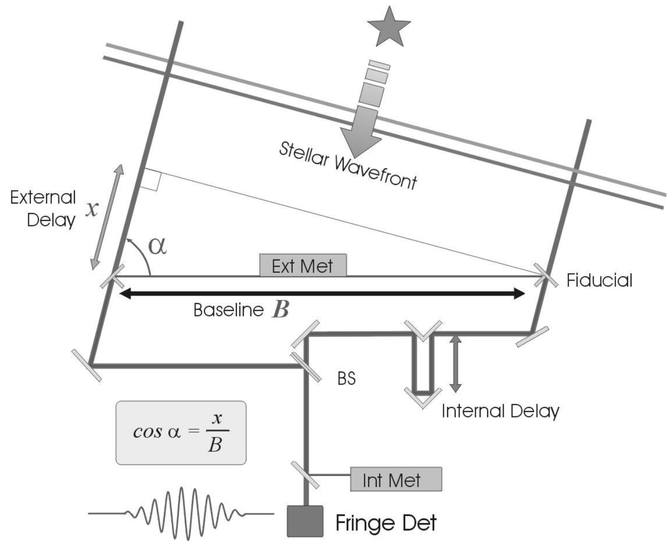

Figure 2 – Astrometry with a stellar interferometer. The starlight fringe contrast is maximum when the internal delay matches the external delay.

PQL simultaneously employs two stellar interferometers and one telescope to perform astrometry. Precision astrometry requires knowledge of the baseline orientation to the same order of precision as the astrometric measurement. To achieve this, a second stellar interferometer is required to measure the baseline orientation in the most sensitive direction and a high-precision telescope to measure the baseline orientation in the other two directions. The second interferometer and the precision telescope acquire and lock on bright "guide" stars, respectively named “guide 1” and “guide 2”, keeping track of the uncontrolled rigid-body motions of the instrument, while the main interferometer switches between science targets, measuring projected angles between them.

To achieve maximum accuracy the stars observed with the science interferometer shall be limited to a 1 degree radius field around the Guide 1 star. A 1 micro-arcsecond error in the measurement of the position of the Guide 1 star produces a 1 micro-arcsecond error on the estimation of the position of the science star, while a 1 micro-arcsecond error in the measurement of the position of the Guide 2 star produces only a 0.007 micro-arcsecond error on the estimation of the position of the science star. This 140 times relaxation on the required accuracy of the Guide 2 star measurement was the big driver for descoping SIM PlanetQuest’s third interferometer to a single telescope on PQL. The Guide 2 scale factor however, increases linearly with the angular separation from the science star to the guide 1 star, adding constraints on how PQL can use its 15 degrees field of regard to do astrometry.

$$\text{Guide 2 multiplier} = \sin(\alpha)/\sin(\varphi) \quad (0)$$

A simple error budget in Figure 3 shows how the 1.4 micro-arcsecond accuracy is sub-allocated between the various sensors.

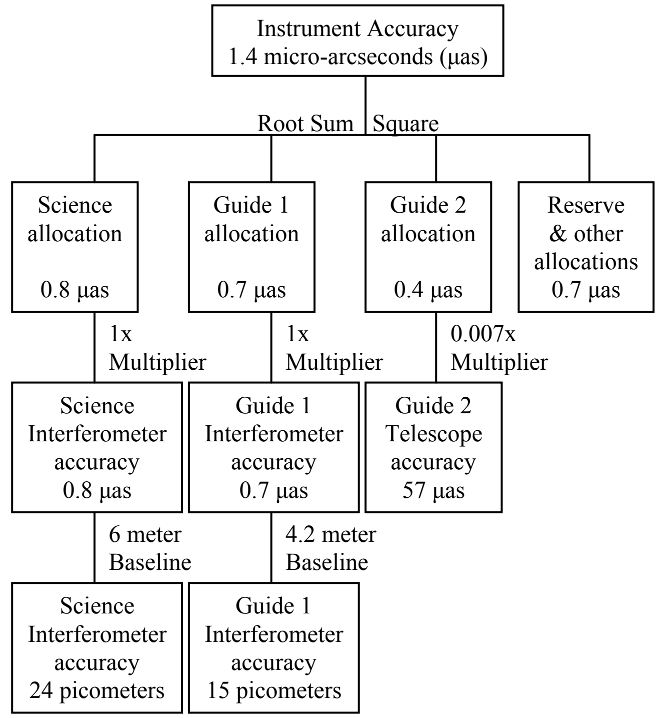

Figure 3 – Simplified PHL astrometric error budget.

Overall configuration

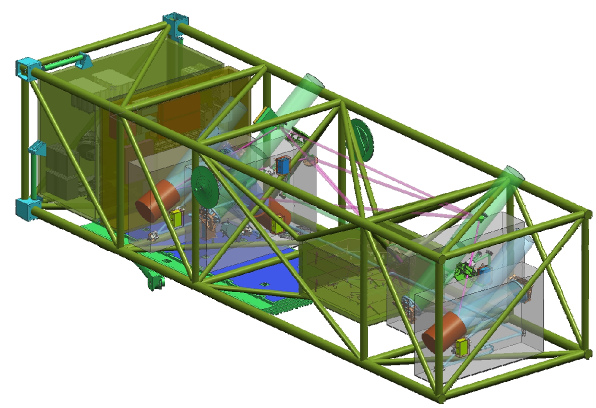

Figure 4 – Conceptual configuration of Planet Quest Light.

Science Interferometer

The science interferometer consists of two 30 cm siderostats separated by a 6 meter baseline. Light reflecting from the two siderostats is collected by telescopes and propagated by a set of optics to the beam combiner where it is re-combined, forming interference fringes. The siderostats have an angular range of articulation that enables acquisition of stars in a 15 degree diameter field in order to build the grid described in the “Global astrometric grid” section of the paper. An optical delay line system with a 0.8 meter travel range produces an internal delay that enables fringe acquisition in that 15 degree diameter field of regard.

Guide 1 Interferometer

The guide 1 interferometer consists of two fixed 30 cm telescopes separated by a 4.2 meter baseline. Light collected by the telescopes propagates through a set of optics to the beam combiner where it is re-combined, forming interference fringes. The Guide 1 has a very narrow field of regard of only a few arcseconds, just enough to compensate for errors in pointing the entire spacecraft.

Guide 2 Telescope

The guide 2 telescope consists of a 30 cm siderostat and a 30 cm confocal telescope, similar to the other 4 telescopes in the science and guide 1 interferometers. Light collected by the telescope reflects on the fine steering mirror and propagates directly to the pointing detector as shown in Figure 5. The metrology system in the Guide 2 telescope is designed slightly differently in order to measure tip-tilt instead of piston.
As the attitude of PQL changes in inertial space, the fine steering mirror (FSM) mechanism tracks the Guide 2 star. Both the CCD based pointing sensor and the metrology system tracking the angular position of the FSM have accuracy close to 10 micro-arcseconds over short time periods.

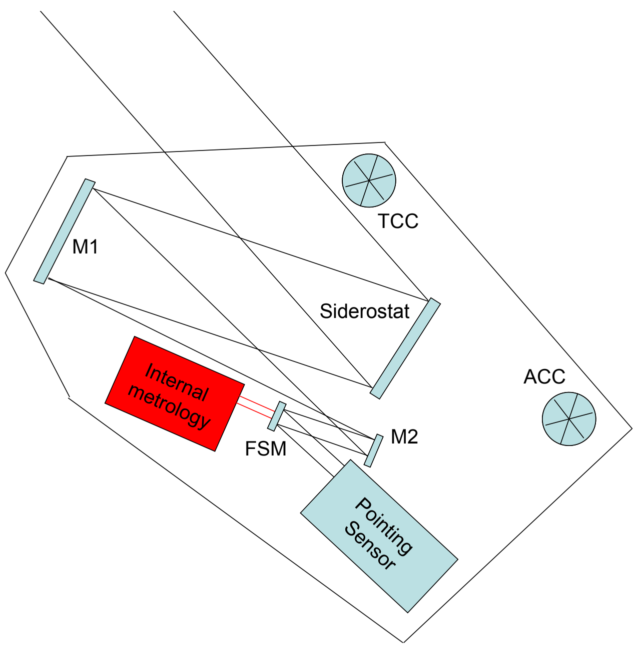

Figure 5 – Guide 2 Telescope layout.

Metrology Truss

The PQL metrology truss has 5 nodes:
- two fiducials in front of the science interferometer collecting mirrors, which define the Science baseline,
- two fiducials in front of the guide 1 interferometer collecting mirrors, which define the Guide baseline,
- one fiducial out of the common baseline plane, which is called the apex corner-cube.

One of the guide 1 fiducials and the apex corner-cube are attached to the Guide 2 telescope. The nominal line of sight of the Guide 2 telescope is aligned with the metrology truss link between this guide 1 fiducial and the apex corner-cube.

3. Astrometric Performance

The 5 year mission will be divided in a few major programs. Table 1 shows the draft allocations:

Table 1 – Mission time allocation.

Task	Targets	Mission
Tier 1 (1Earth)	56 stars	46%
Tier 2	1050 stars	5%
Young Stars	67 stars	2%
Grid	44,000 tiles	9%
Quasars	50 quasars	1.5%
Wide Angle	8,300 hours	19%
S/C Slewing	61,100 slews	14%
Alignment/Cal	50 min/day	3.5%

Deep planetary survey

The deep planetary survey (also known as Tier-1 survey) will focus on relatively few (less than one hundred) nearby stars of the main sequence (G, K and M types), within 10 parsecs from the Sun. The main objective is to identify planetary system with Earth-like planets in the habitable zone around these Sun-like stars.

The deep survey requires the highest possible astrometric accuracy, at or below one micro-arcsecond. This accuracy is achieved by multiple visits to the target stars. Planet Quest Light will achieve 2 micro-arcsecond differential error between Tier 1 target position and a set of reference stars per 12-chop visit. Most Tier-1 targets will require more than 12 chops per visit, the average being around 72 chops per visit, in order to reduce the instrument accuracy down to the required level for detection of 1-Earth mass planet. A 72 chop visit to a magnitude 6 Tier 1 Target would require less than two hours of observation time.

Figure 6 illustrates the sequence used for the narrow angle observation. The sequence starts with 20 seconds of observation time on the target star, T, during which interference fringes are collected. The observation is followed by about 15 seconds to slew and reposition the two siderostats and the optical delay line to acquire fringes on the first reference star, R2. After 40 seconds of observation on R2, the interferometer is slewed back to the same target star T, which is re-observed for 20 seconds.

Then, the instrument is slewed to the second reference star, R3, which is observed for 30 seconds, and next slewed back to the target star. We continue slewing and observing between the target stars and the other reference stars R4 and R5. Finally, we repeat the sequence from the beginning. During the entire sequence, the Guide 1 interferometer and the Guide 2 telescope are locked on their respective stars, monitoring changes of the instrument attitude in inertial space.

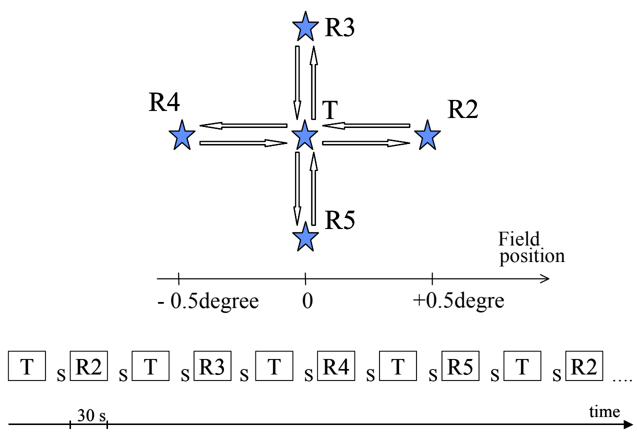

Figure 6 – Narrow Angle observation sequence.

In order to determine accurately the orbit parameters of the planets, 200 visits per Tier 1 target star will be scheduled over the 5 year mission, 100 visits in each of two orthogonal baseline orientations.

The PQL design imposes several constraints on the selection of the Tier 1 targets:
- First, the Tier 1 Target star V magnitude shall be brighter than 6. Figure 7 shows a histogram of 65 candidate Tier 1 targets, all of which meet this constraint.
- Second, at least three reference stars of V magnitude brighter than 9 can be found in a 1.25 degree radius field around the Tier 1 target star. Figure 8 shows a histogram of the mean reference star flux for 28 reference star groups. This constraint is met for all but three of the Tier 1 targets.

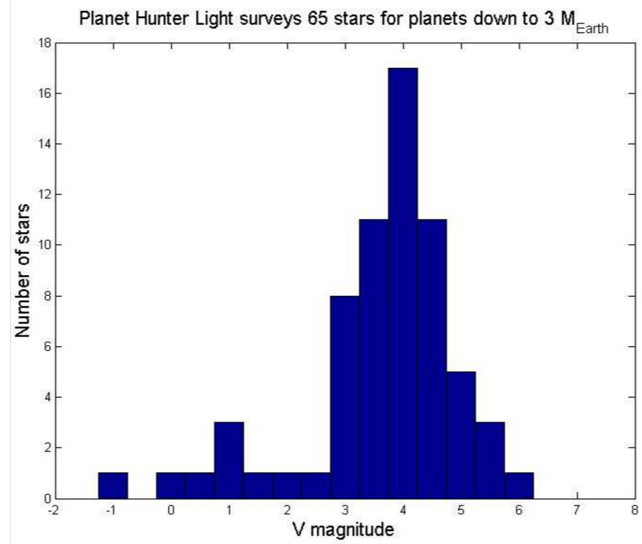

Figure 7 – Target star V magnitudes.

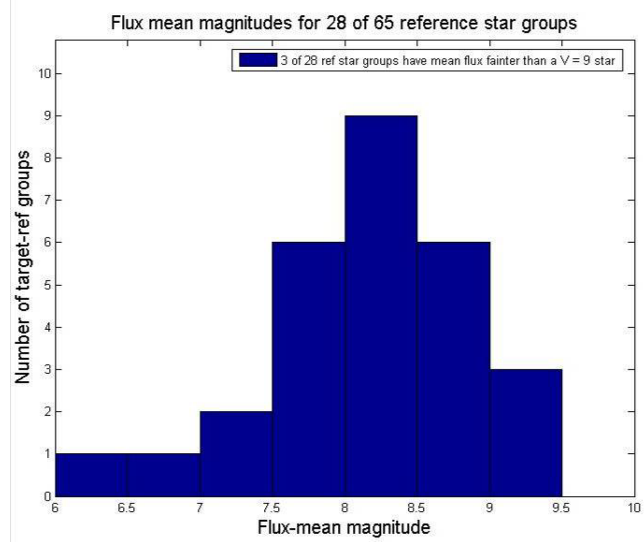

Figure 8 – Mean reference star flux for 28 reference star groups.

The team is currently proposing that 46% of the mission time be allocated to the deep planetary survey.

Timing requirements for a typical 12 T-R-T chop visit:
- 360 seconds of retargeting time between stars (24 times 15 seconds).
- 240 seconds of total integration time on the Tier 1 target per visit (12 times 20 seconds).
- 480 seconds of total integration time on the set of Reference stars (12 times 20 seconds).

The total scheduled time per 12-chop visit to a Tier 1 target is 1,080 seconds and increases to 6,480s for a 72 chop visit. The number of Tier 1 targets that can be surveyed is estimated as follows:

$$46\% * 5y*365d*86{,}400s / 6{,}480s / 200visits \sim 56 \text{ stars} \quad (2)$$

Broad planetary survey

The Broad planetary survey (also known as Tier-2 survey) will focus on a larger set of stars (numbering over a thousand) of many types (including O, B, A, F, binary) to cover the diversity of planetary systems [2]. The main objective is to increase our knowledge on the nature and evolution of planetary systems in their full variety.

The broad survey can be achieved with astrometric accuracy of five micro-arcseconds, which can be achieved by short visits to the target stars. Planet Quest Light will achieve an instantaneous 5 μas differential error between Tier 2 target position and a set of reference stars with a single 60 second visit.

In order to determine accurately the orbit parameters of the planets, 100 visits per Tier 2 target star will be scheduled over the 5 year mission, 50 visits in each of 2 othogonal baseline orientations.

The PQL design imposes a few constraints on the selection of Tier 2 targets:
- First, the Tier 2 Target star V magnitude shall be brighter than 10.5, in order to limit the observation time to 60 seconds per visit.
- Second, to maximize the instrument efficiency, the Tier 2 target needs to be located near a Tier-1 target star from the deep survey. By doing so, no additional mission time is required to point the space-craft toward the Tier-2 target and the same set of reference stars can be used. The number of Tier-2 targets being about ten times the number of Tier-1 targets, we would need to observe an average of ten Tier-2 targets around each Tier-1 star. Allowing the instrument to observe Tier-2 targets at up to 2.5 degrees away from the Tier-1 stars opens a sky field of about 20 square degrees per Tier-1 star. The broad survey would be achievable if the density of Tier-2 stars is greater than 0.5 stars per square degree. Figure 9 shows the star density for Tier 2 targets up to magnitude 10 versus distance. The curve indicates that we would have to extend the survey to at least 400 parsecs. However, increasing the magnitude to 10.5 should yield the required density of candidates.

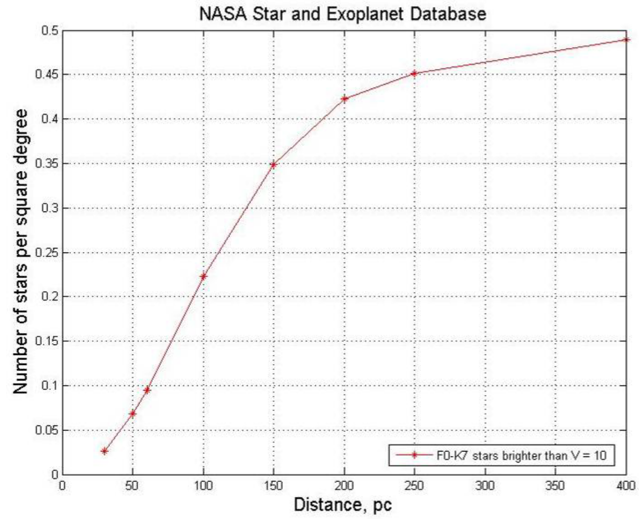

Figure 9 – Tier-2 target star density versus distance from the Sun.

The team is currently proposing that 5% of the mission time be allocated to the broad planetary survey.

Timing requirements for a visit to a typical magnitude 10.5 Tier-2 target:
- 15 seconds retargeting time to acquire the Tier-2 star.
- 60 seconds of integration time on the Tier-2 target.

The total scheduled time per visit to a Tier 2 target is 75 seconds. The number of Tier 2 targets that can be surveyed is estimated as follows:

$$5\% * 5y*365d*86{,}400s / 75s / 100visit \sim 1050 \text{ stars} \qquad (3)$$

Young planetary systems

The young planetary system survey (also known as Young star survey) will focus on relatively few (less than one hundred) nearby solar type stars with ages below 100 million years, within 100 parsecs of the Sun. The main objective is to understand the frequency of Jupiter-mass planets and the early dynamical evolution of planetary systems.

This young planetary system survey can be achieved with astrometric accuracy of four micro-arcseconds. Planet Quest Light will achieve the 4 μas differential error between the young star position and a set of reference stars with 4-chops for every visit. A 4 chop visit to a magnitude 11 young star requires about eight minutes of observation time.

In order to determine accurately the orbit parameters of the planets, 100 visits per young star will be scheduled over the 5 year mission, 50 visits in each of 2 othogonal baseline orientations.

The PQL design imposes several constraints on the selection of the young planetary systems:

- First, the young star V magnitude shall be brighter than 11. Figure 10 shows the number of candidate young stars versus magnitude. About 80 candidates meet this constraint.

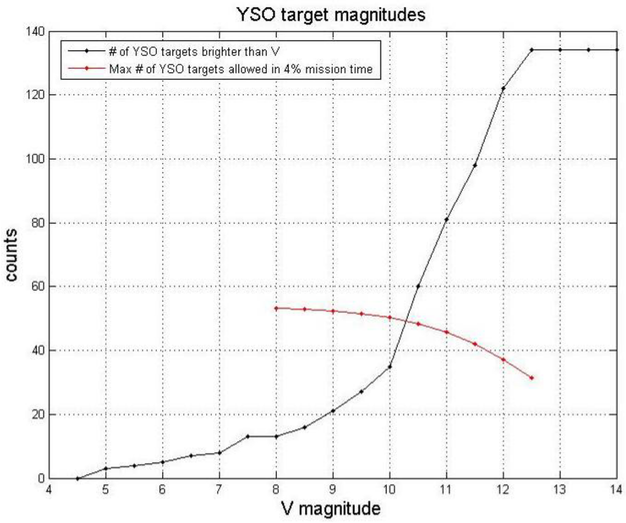

Figure 10 – How many targets can be in the Young Star Survey?

- Second, at least one guide star of V magnitude brighter than 7 must exist within a 1 degree radius field around the young star. Most of the young stars are fainter than 7th magnitude, so they are not suitable candidates for tracking the attitude of the Guide baseline. There are 15,600 stars brighter than V=7 in the sky. Table 2 shows the average number of stars brighter than V=7 versus field size.

Table 2 – Number of candidate Guide stars of magnitude greater than 7 versus size of the field of regard.

Radius, degrees	1	1.25	1.5	1.75	2.0
Number of candidate guide stars	1.2	1.9	2.7	3.6	4.8

- Third, at least three reference stars with V magnitude brighter than 9 must exist within a 1.25 degree radius field around the young star. This magnitude constraint on the reference stars is met for all Tier 1 targets and will likely be met for all the young stars too.

The team is currently proposing that 2% of the mission time be allocated to the young planetary system survey.

Timing requirements for a typical 4 T-R-T chop visit:
- 120 seconds of total retargeting time between stars.
- 250 seconds of total integration time on the young star.
- 100 seconds of total integration time on the set of Reference stars.

The total scheduled time for a visit to a young star is 470 seconds The number of young star targets that can be surveyed is estimated as follows:

$$2\% * 5y*365d*86{,}400s / 470s / 100visit \sim 67 \text{ stars} \quad (4)$$

Global astrometric grid

Most of the non-planetary astrophysics programs that PQL will execute rely on an absolute reference frame called the grid. PQL will build an all-sky astrometric grid consisting of about 1300 pre-selected stars and about 50 quasars, with an end of mission accuracy of 6 micro-arcseconds in positions at the mean epoch and in parallaxes.

The full field of regard of PQL is 15 degrees in diameter, covering about 6 grid stars in average at any position of the sky. PQL will observe the grid stars sequentially, going through the 1300 tiles centered on the 1300 grid stars. During the 5 years, PQL will go 34 times through the set of 1300 tiles. Since during each tile, an average of 6 grid stars will be observed, at the end of 5 years, each grid star will have been observed 34*6 ~ 200 times.

The set of grid stars already identified for SIM Planet Quest is fully appropriate for PQL. The key criteria for the selection were that the grid stars be K giant stars, at least 500 parsecs away, with no known stellar companions, distributed quasi-uniformly over the sky to maximize the grid stability and performance. The set of 1300 grid stars has a median magnitude of V = 9.9. One additional criteria is the existence of a guide star of V magnitude brighter than 7 within in a few degrees of each grid star. The majority of the grid stars have magnitudes in the V = 9 – 10.5 range, therefore they are not suitable for tracking the attitude of the Guide baseline.

Each visit to a typical tile will consist of a single G1–G2–G3…G6–G1 chop through the 6 grid stars. The time required for a visit to a tile of magnitude 10.5 grid stars is:
- 210 seconds of total retargeting time between 6 grid stars.
- 105 seconds of total integration time on the set of grid stars.

The total scheduled time for a visit to a tile is 315 seconds. The grid campaign will be completed after 34 visits to the 1300 distinct tiles over the 5 year mission. The fractional mission time required to complete the 44,000 tiles is estimated as follows:

$$34visits * 1{,}300tiles * 315s / 5y*365d*86{,}400s \sim 9\% \quad (5)$$

The grid will be anchored to an absolute inertial reference frame consisting of a set of distant quasars. Observing the 50 quasars will require an additional 1.5% of the mission time.

Wide angle astrometry

The Wide Angle astrometry program covers a wide range of topics in Galactic and extragalactic astronomy, such as formation and dynamics of our Galaxy, calibration of the cosmic distance scale, and fundamental stellar astrophysics. For bright objects up to magnitude 14, the global astrometric performance will be limited to the 6 micro-arcseconds end of mission grid error. For dimmer stars, the astrometric performance would vary depending on the observation time allocated to the object, reaching 30 micro-arcseconds on magnitude 20 objects after about 50 hours of integration.

In order to adequately measure parallax and proper motion, an average of 100 visits per object will be scheduled over the 5 year mission, 50 visits per baseline orientation. The integration time on the object for each visit will vary with magnitude and expected performance, all the way to two hours on the dimmest objects. There is no hard limitation on the magnitude, but integration time for objects fainter than magnitude 20 require hours just for initial acquisition of the fringes.

Planet Quest Light like SIM Planet Quest would allocate 19% of the 5 year mission to Wide Angle astrometry. The corresponding 8,300 hours would be allocated based on Table 3.

Table 3 – Total observation time (hours) versus measurement accuracy.

Magnitude	10	12	14	16	18	19	20
6 µas	1.2	2.9	14.2				
8 µas	0.15	0.29	1.0	5.8			
10 µas	0.13	0.15	0.49	2.7	20.8		
12 µas		0.13	0.32	1.7	12.6		
15 µas			0.24	1.1	7.9	33.5	
20 µas			0.18	0.77	5.2	17.7	
30 µas			0.14	0.51	3.4	9.3	39.4
40 µas				0.40	2.6	7.1	21.7
50 µas					2.2	5.9	16.7

Non-observational time

The total number of spacecraft maneuvers required to re-point the instrument to new star fields to complete the various observation programs is shown in Table 4. The average slew angle will be 7 degrees. It will take on average 6 minutes to slew the spacecraft through an angle of 7 degrees and to settle the instrument attitude at the end of the maneuver.

Table 4 – Total required number of spacecraft maneuvers to complete the PQL mission.

Task	**Targets**	**Visits**	**S/C Slews**
Tier 1 (1Earth)	56 stars	200	11,200
Young Stars	67 stars	100	6,700
Grid	1,300 tiles	34	44,000
Grid overlap	– 24 tiles	34	– 800
Total			61,100

For the estimation of the required number of spacecraft maneuvers, we assume that the observations of the Planetary Broad Survey targets, the Quasars and Wide Angle Astrometry targets do not require additional dedicated slews. If stars were uniformly sampled on the sky, 48 of the 1300 grid stars would be located within 2 degrees of targets of the Young Planetary System or Deep Planetary Surveys[4]. A more realistic assumption is that only half of the 48 grid stars will be within 2 degrees of the Planetary targets, making the overlap between the Grid campaign and the planetary surveys only 24 tiles.

The total mission time to be allocated for spacecraft maneuvers is 14% of the mission:

$$61{,}100\text{slews} * 360\text{s} / 5\text{y}*365\text{d}*86{,}400\text{s} \sim 14\% \qquad (6)$$

6. Conclusion

Although Planet Quest Light will not achieve the full science program planned for SIM PlanetQuest, a large portion of it, arguably 50%, could be completed. The cost on the other hand will make PQL a much more affordable mission in which NASA can invest in the next few years.

Acknowledgements

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1,300 grid stars/40,000deg^2 * (56+67) planetary targets*12deg^2 ~ 48

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BIOGRAPHY

Dr. Renaud Goullioud *has an electronics engineering degree from the Institute of Chemistry and Physics of Lyon, France, and a Ph. D. in micro-electronics from the National Institute of Applied Sciences of Lyon. He has been working at Jet Propulsion Lab on the Space Interferometry Mission since 1997. He has been a key contributor to SIM's ambitious technology development, demonstrating path length feed-forward control among three interferometers on the STB–3, picometer-level sensing on SIM-like interferometer in the MAM testbed and picometer-level wavefront stability on a flight-like telescope in the TOM3 testbed. He is currently acting as the SIM–PlanetQuest Instrument Manager.*