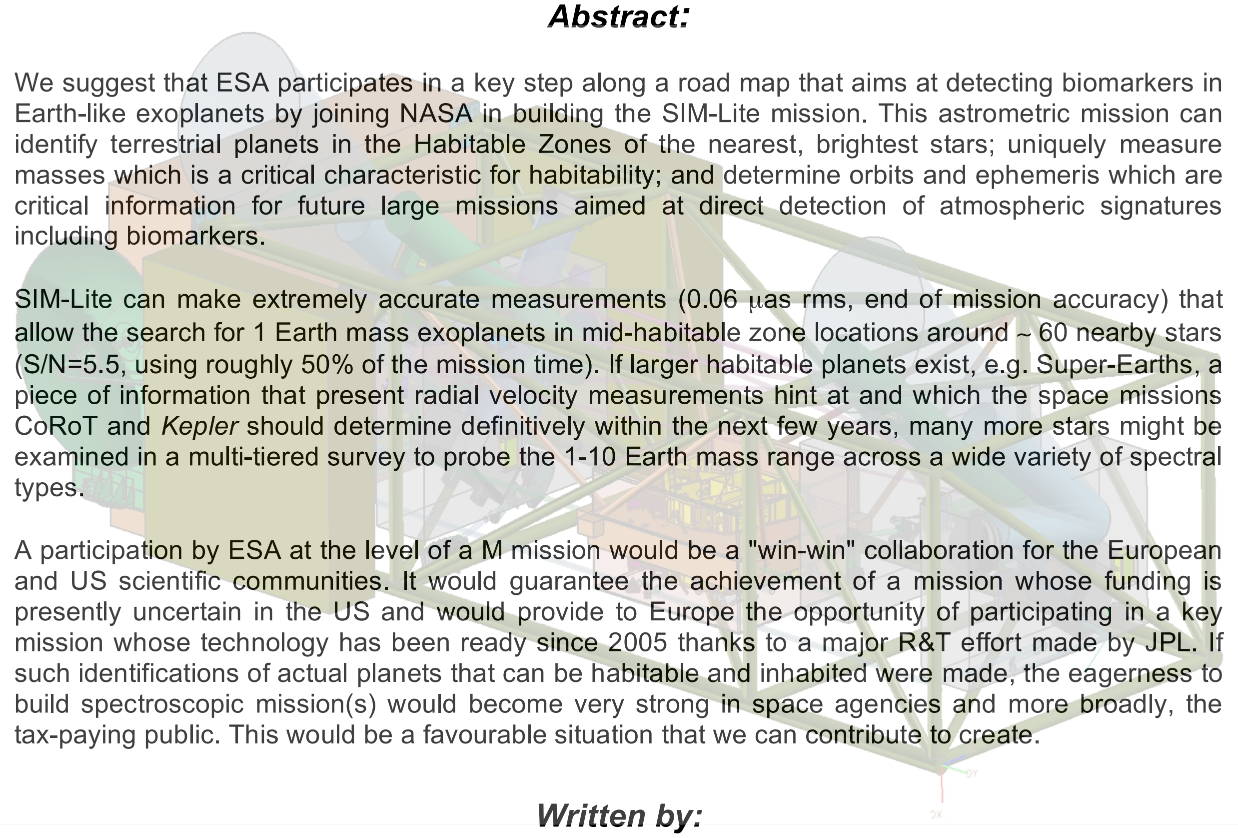
Science and Programmatic Cases for ESA Participation in the SIM-Lite Mission



Abstract:

We suggest that ESA participates in a key step along a road map that aims at detecting biomarkers in Earth-like exoplanets by joining NASA in building the SIM-Lite mission. This astrometric mission can identify terrestrial planets in the Habitable Zones of the nearest, brightest stars; uniquely measure masses which is a critical characteristic for habitability; and determine orbits and ephemeris which are critical information for future large missions aimed at direct detection of atmospheric signatures including biomarkers.

SIM-Lite can make extremely accurate measurements (0.06 μas rms, end of mission accuracy) that allow the search for 1 Earth mass exoplanets in mid-habitable zone locations around ~ 60 nearby stars (S/N=5.5, using roughly 50% of the mission time). If larger habitable planets exist, e.g. Super-Earths, a piece of information that present radial velocity measurements hint at and which the space missions CoRoT and *Kepler* should determine definitively within the next few years, many more stars might be examined in a multi-tiered survey to probe the 1-10 Earth mass range across a wide variety of spectral types.

A participation by ESA at the level of a M mission would be a "win-win" collaboration for the European and US scientific communities. It would guarantee the achievement of a mission whose funding is presently uncertain in the US and would provide to Europe the opportunity of participating in a key mission whose technology has been ready since 2005 thanks to a major R&T effort made by JPL. If such identifications of actual planets that can be habitable and inhabited were made, the eagerness to build spectroscopic mission(s) would become very strong in space agencies and more broadly, the tax-paying public. This would be a favourable situation that we can contribute to create.

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1. A possible Road Map

Although not unique, a sensible road map to characterize habitable planets is:

(1) A statistical determination of the frequency of habitable planets;

(2) The identification of potentially habitable, terrestrial planets around nearby stars that would be suitable for investigation by future spectroscopic missions;

(3) Spectroscopic studies of these planets with the aim of identifying key atmospheric gases for comparative planetology and search for life.

Step (1) should be achieved by already planned missions as *Kepler* (launch Feb. 2009). The goal of the present White Paper is to discuss the best way to achieve step (2).

In another white paper called "*Identifying nearby Earth-size planets in the Habitable Zone that can be targets for spectroscopic studies*", we have shown that the method to detect Earth-size planets in the Habitable Zone (HZ) of nearby stars that is the least sensitive to stellar activity biases is **astrometry**. The corresponding estimates are only indicative but point to the interest of building an astrometry instrument. This is the goal of the SIM-Lite project by NASA.

2. Schematic description of the SIM-Lite instrument

2.1 Astrometry with an interferometer

The reflex motion of a nearby star in the presence of a telluric planet in its HZ is quite small, typically 0.3 μas for a 1 M_{Earth} planet around a sun at 10 pc. For comparison, this angle corresponds to an interval of 0.6 mm seen from the Earth-Moon distance!

The principle of SIM-Lite is to make extremely precise measurements of the Optical Path Difference between the Delay Lines that provide the scanning of the fringe pattern (Goullioud et al. SPIE 2008, arXiv:0807.1668; Fig. 1). Differential measurements with an accuracy of 0.57 μas between a target star ($V<8^{th}$ mag) and four distant (0.5-1 kpc; V~10 mag) reference stars located 1-2 degrees away on the sky are performed on a roughly 2 hour cycle. For stars brighter than $V\sim8^{th}$ mag the majority of the observing time is spent on the fainter reference stars. The requirement on the metrology to achieve the requisite sub-micro-arcsecond accuracy is 10 pm. During a major R&T study, laboratory demonstrations at JPL have shown that this accuracy can be achieved and even significantly exceeded (3 pm precision has been obtained).

However, the accuracy obtained during a single measurement cycle is not sufficient to detect an earth analogue (typically 0.3 μas). About 100 independent cycles would be necessary to obtain a SNR of 5.5. A major result of the laboratory study is that this ultimate accuracy is possible because *systematic errors in this differential mode are extremely small*, less than 0.05 μas. These independent measurements must be spread out over a period of several years in order to obtain the relevant planetary orbit parameters (Sect.3.1).

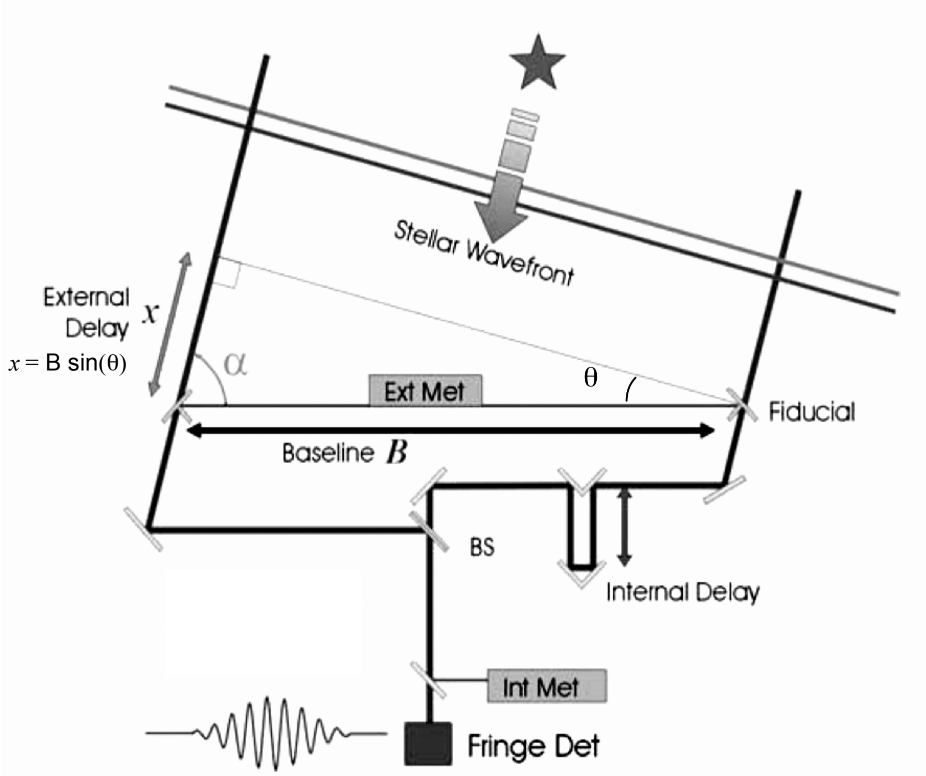


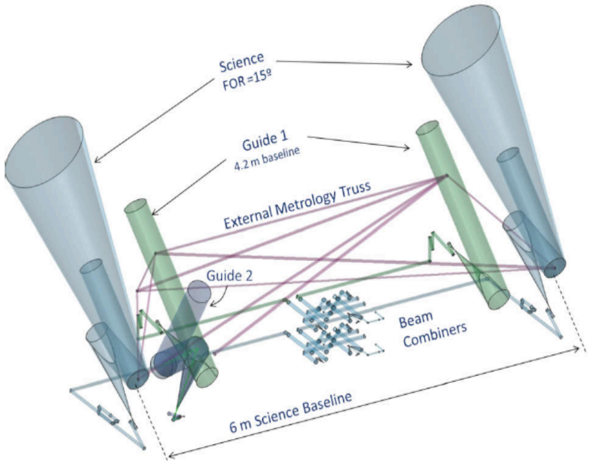
Figure 1: Diagram of the measurement of the angle between a stellar direction and that of the interferometer base, thanks to a precise location of the fringe pattern.

2.2 The SIM-Lite instrument

Fig.2 shows views of the SIM-Lite spacecraft. A 6 m carbon boom supports (1) the mechanically insulated platform (power supplies, avionics, electronics…), (2) the scientific interferometer with its siderostats and 30 cm (possibly 50 cm) telescopes, (3) the guiding interferometer and telescope.

2.3 The technology needed for SIM-Lite is ready

As a result of a major effort of ***300 M$,*** implying an average of ***50-100 people working during 10 yrs***, JPL has demonstrated that the ***technology for SIM-Lite is ready***. Engineering models of many key optical components, such as picometer laser gauges, metrology source, triple corner cube optical fiducials, have been built and tested to work to survive launch and work in a space environment. System level testbeds were built and operated to demonstrate sub-microarcsec precision (Fig. 3). Using artificial stars, the latter has demonstrated that the required accuracy for differential angular measurements can be reached, and even exceeded, in a 2° field of view. The technology maturity level TR6 was demonstrated with extensive external peer review in 2005.



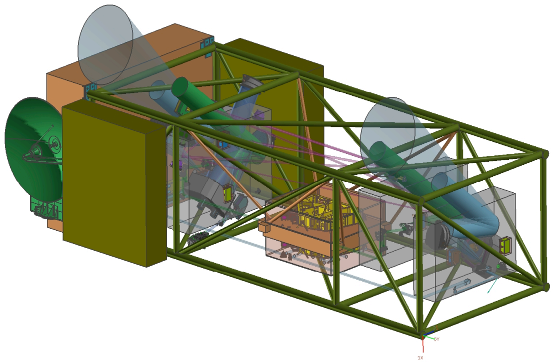


Figure 2: diagrammatic and artist views of the SIM-Lite spacecraft

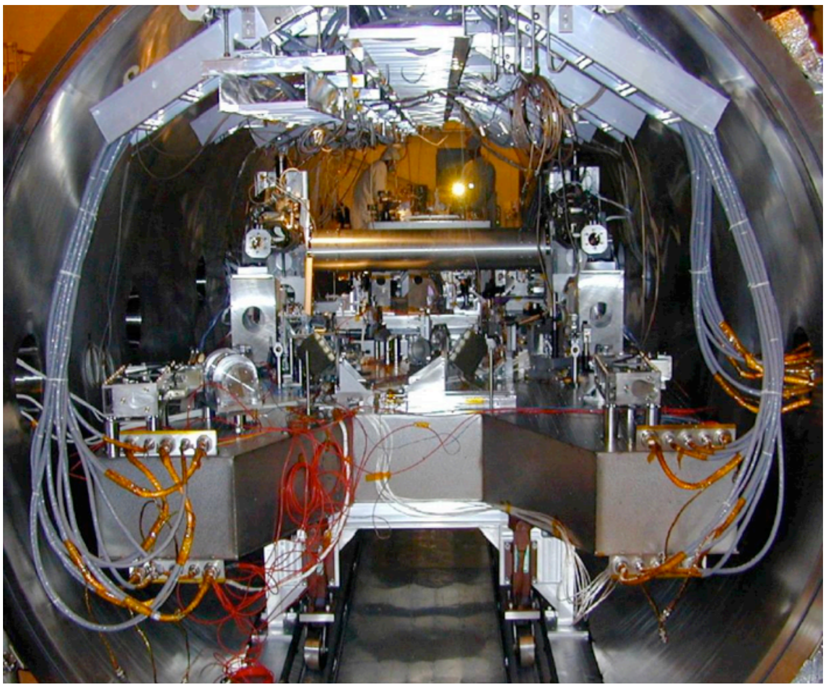


Figure 3: part of the Micro Arcsec Metrology testbed in its vacuum chamber

3. Planet detection around nearby stars using SIM-Lite

3.1 Strategy

The astrometric displacement induced by a planet in the HZ of a star is

$$A = 0.30\ (M_{pl}/M_{st})\ (M_{st}/M_0)^{-1}\ (D/10\ pc)^{-1}\ (L_{st}/L_0)^{1/2} \quad \mu as \qquad (1)$$

where M_{pl}, M_{st} and M_0 are the planet, star and Sun masses, D is the distance of the system, and L_{st} the stellar luminosity. As indicated in the target list (Table 1), for many target stars, this displacement is smaller than the noise after one measurement cycle (0.57 μas for a V = 6-8 mag star). However, after 100 such cycles are performed during the whole mission duration (5 yrs), an Earth mass planet can be detected with S/N ~ 5.5 (nominal case of Eq.1 and corresponding to a false alarm probability of 1%). In addition to the simple detection, its mass, orbit and its ephemeris are determined (Fig.4), which are critical information for the characterization of the planet and very practical for the optimization of the measurements by future spectroscopic missions.

3.2 How many stars can be explored by SIM-Lite?

Table 1 gives a possible target list of 60 stars. The ranking is made by increasing integration time required to detect a 1 M_{Earth} planet in the HZ of the star (SNR = 5.5, corresponding to a risk of false detection of 1%). It is noteworthy that exploring the first 30 stars requires 6 months of integration whereas detecting the next 30 stars requires additional 15 months. More massive planets, e.g. Super-Earth with M_{pl} = 3 M_{Earth}, are detected much faster.

The astrometric displacement of a star is dominated by its most massive and most distant planets. While the effect of telluric planets in its HZ is significantly weaker than that of more distant giant planets, the presence of giant planets should not be a major problem for two reasons: (1) by the time SIM-Lite will fly, RV studies extending over 15 – 20 yrs for all key nearby stars will have identified and characterized giant planets with periods less than 10 yrs; (2) the period of a telluric planet in the HZ, e.g. ~ 1 yr, is significantly smaller than that of distant giants (≥ 5 yrs). Different planets will be well separated in frequency space; (3) we know from RV studies that the fraction of stars having giants in the 1-5 AU range is rather small (< 10%).

The Michelson Science Centre has initiated a blind detection exercise in 2008 in order to test the possibility of detecting the presence of earths in the presence of other planets in different configurations, using simulated astrometric data. It should qualify/falsify the above qualitative arguments.

3.3 Other programs by SIM-Lite

SIM-Lite is planned to operate during a 5-yr period with a possible extension to 10 years. In addition to the key program of a high accuracy survey (0.06 μas) described here, a broad survey (5 μas, 1000 stars) is foreseen searching for larger planets as well as a survey around young stellar objects (60-100 stars). SIM-Lite would also be capable of a general astrophysics program to study Galactic and extragalactic objects at the 4 μas level for sources as faint as V~19 mag. Such a program would be ***highly complementary to GAIA.*** SIM-Lite will study clearly fewer objects than will GAIA, but with the higher astrometric precision and user-determined cadence possible with a pointed observatory compared to a scanning sky survey mission.

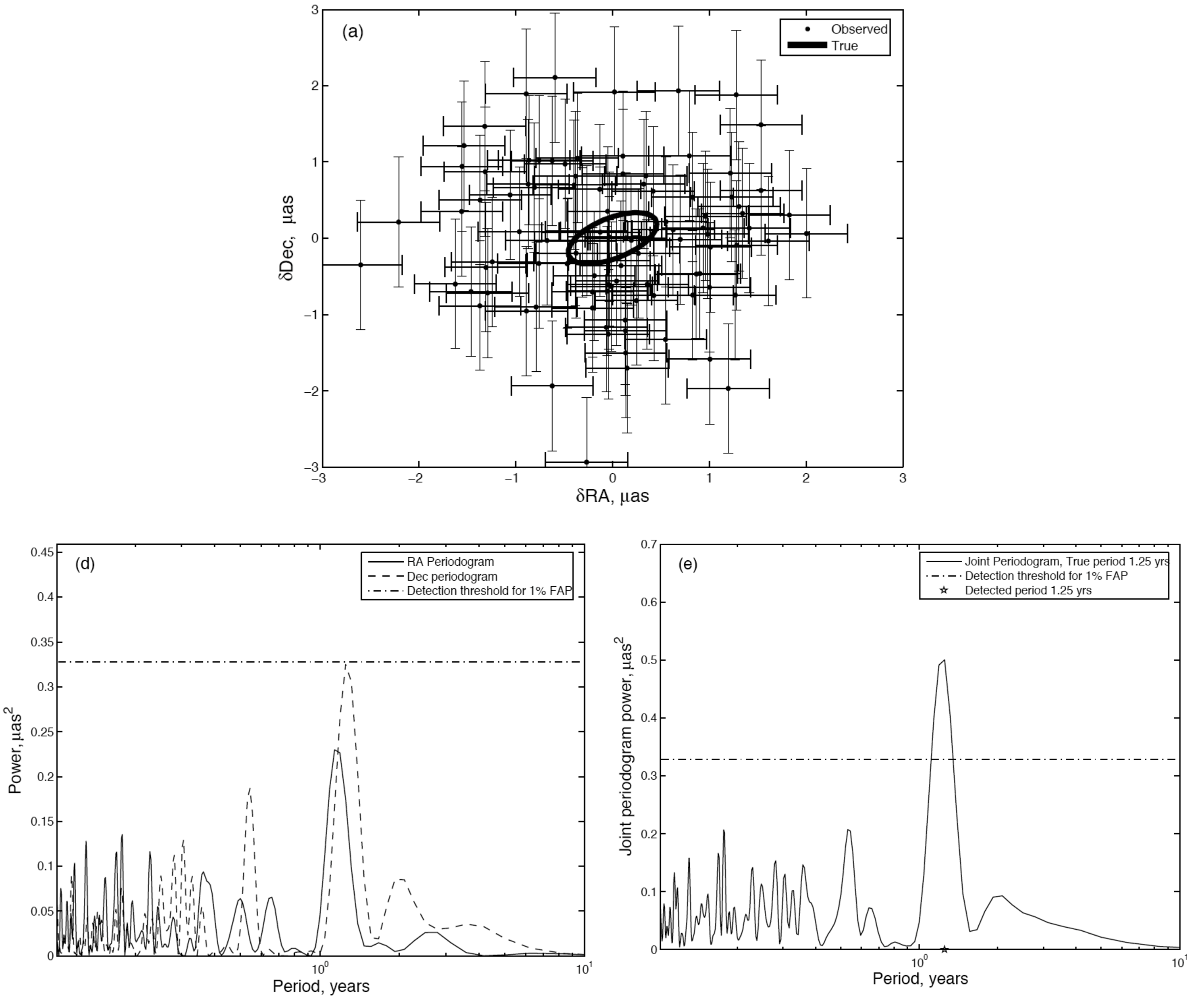


Figure 4 : Simulation of the detection by SIM-Lite for a 1.5 M_{Earth} planet at 1.16 AU from a 1 M_0 star at 10 pc. (a) Actual orbit of the planet projected on the sky and 2x100 measurements, with +/- 1 σ error bars, of its positions during a 5 yr period, in Dec and RA. No detection is possible without fitting the data to a model of a Keplerian orbit. (d) Periodogram of these measurements in Dec and RA, respectively. (e) Joint periodogram. A peak is clearly detected in the latter above the threshold corresponding to a 1% risk of false alarm. Then a fit is performed of the 2 x 100 measurements on a Keplerian orbit with known period in order to determine the different parameters of the orbit (a, e, i,…) and the ephemeris of the planet. The planetary mass is deduced from that of the star.

4. The possible role of ESA in the SIM-Lite project

4.1 Situation of SIM and SIM-Lite in the US

The costing of the initial SIM (SIM/PlanetQuest) project appears to be too high for the present funding situation at NASA. Consequently, the project and science team have worked on a less costly version of the project, SIM-Lite. The cost of the mission is significantly reduced, approximately by a factor of 2, because demonstrated advances in the technology program have allowed a simpler design concept to achieve the overall mission goals. SIM-Lite uses a reduced number of high accuracy interferometers operating with a smaller boom, 6 m instead of 9 m. These changes reduce the mass and complexity of the instrument and avoid the need for building new test facilities while preserving the narrow-angle and wide-angle performance goals approved by two reviews by the US National Academy. However, even in this reduced configuration, the cost estimates for SIM-Lite will exceed that of the "Probe-Class" mission presently under consideration by NASA (600 M$).

4.2 A win-win collaboration

This situation is in fact a ***wonderful opportunity for ESA*** to make possible the achievement of a mission that has a major role in a telluric planet road map. A participation at the level of a M mission would solve the funding problem. It would make possible the building of an extreme instrument in a near future, taking advantage of the achieved 300 M$ R&T study.

What could be the actual contribution of ESA to the project is a major issue that has to be negotiated because a major funding implies a major scientific and technical participation. The basic idea should remain the driving force, making possible *a "win-win" collaboration* for the European and US scientific communities. The situation in the US during the last years has shown that in the absence of a new major participation, SIM, even in its light version is in danger of being frozen and never built. On the ESA side, this is a possibility to participate in the achievement of a major milestone in an exoplanet road map: the detection and orbital characterisation of the planets that can be targets for the future searches for life, thanks to a mission with extreme technology but which is ready today.

One should note that Europe is involved in a large effort for astrometric searches for exoplanets at ESO on the VLTI through the PRIMA project. Therefore one could imagine that this experience could be of interest in the participation of Europe in SIM-Lite at the data reduction level.

4.3 A major impulse to the exo-planetary science

A participation of ESA in the SIM-Lite mission and its achievement within a decade would not only be a step in a sensible exoplanet roadmap, but it would also ***give a major impulse to the exoplanet discipline whole***. If we knew that there are sister planets to Earth around α Centauri, τ Ceti or ε Eridani and many other stars that can be seen with the naked eye, ***the urge to build*** an instrument to investigate their atmospheric compositions and possibly learn if there is life on some of them ***would be extremely strong***, almost irresistible. Within the space agencies as well as among the larger tax-paying public, this goal would be well understood. It would fit the idea of a "Society of the Knowledge" that the European Union wants to build for the future because it addresses one of the longest standing questions in natural philosophy, namely the existence of life beyond the Earth.

It is the opinion of the proposers of this White Paper that the successful launch and operation of SIM-Lite and the resultant detection of many Earth analogues within 15 pc (Table 1) would put the subsequent construction of the first spectroscopic mission, either a visible coronagraph/occulter or an IR interferometer, in a new and highly favourable situation. This would be a favourable situation that we can contribute to create.

July 2008

Table 1

Preliminary target list for SIM-Lite (courtesy of M. Shao)

star#	Name	Hip #	V (mag)	D (pc)	L/L_0	Amp (μas) M_{pl} = 1 M_{Earth}	t_{integ} (hr)	t_{cum} (month)
1	**Alpha Cen A**	71683	0,0	1,3	1,35	2,40	4	0,01
2	**Alpha Cen B**	71681	1,4	1,3	0,34	1,72	7	0,02
3	**Tau Cet**	8102	3,5	3,6	0,39	0,66	51	0,09
4	Beta Hyi	2021	2,8	7,5	3,24	0,53	78	0,19
5	**Eps Eri**	16537	3,7	3,2	0,21	0,64	85	0,31
6	Delta Pav	99240	3,7	6,1	1,02	0,49	90	0,43
7	Pi3 Ori	22449	3,2	8,0	2,86	0,48	95	0,56
8	Epsilon Ind A	108870	4,7	3,6	0,10	0,48	96	0,70
9	Omicron2 Eri A	19849	4,4	5,0	0,29	0,45	111	0,85
10	82 Eri	15510	4,3	6,1	0,54	0,43	120	1,0
11	Beta TrA	77952	2,8	12,3	9,62	0,42	126	1,2
12	Gamma Lep A	27072	3,6	9,0	2,43	0,41	129	1,4
13	Sigma Dra	96100	4,7	5,8	0,32	0,40	139	1,6
14	Beta Vir	57757	3,6	10,9	3,47	0,37	161	1,8
15	Zeta Tuc	1599	4,2	8,6	1,19	0,36	166	2,0
16	Gamma Pav	105858	4,2	9,2	1,44	0,36	174	2,3
17	Beta Com	64394	4,2	9,2	1,33	0,35	179	2,5
18	Gamma Ser	78072	3,9	11,1	2,94	0,35	181	2,8
19	Iota Per	14632	4,1	10,5	2,08	0,34	191	3,0
20	13 Per	12777	4,1	11,2	2,36	0,33	205	3,3
21	61 Vir	64924	4,7	8,5	0,68	0,32	212	3,6
22	Eta Lep	28103	3,7	15,0	6,43	0,31	229	3,9
23	Kappa1 Cet	15457	4,8	9,2	0,73	0,30	238	4,3
24	(no name)	57443	4,9	9,2	0,72	0,30	243	4,6
25	Upsilon And A	7513	4,1	13,5	3,36	0,30	249	4,9
26	Alpha Crv	59199	4,0	14,8	4,65	0,29	257	5,3
27	Iota Psc	116771	4,1	13,8	3,48	0,29	257	5,6
28	(no name)	114622	5,6	6,5	0,15	0,29	257	6,0
29	KX Lib	73184	5,7	5,9	0,09	0,29	260	6,4
30	23 Boo	70497	4,0	14,6	4,19	0,29	262	6,7
31	Psi Cap	102485	4,1	14,7	4,03	0,28	271	7,1
32	Alpha Tri	8796	3,4	19,7	13,76	0,28	272	7,5
33	Zeta Dor	23693	4,7	11,7	1,45	0,28	277	7,9
34	10 Tau	16852	4,3	13,7	2,88	0,28	278	8,3
35	I Car	50954	4,0	16,2	5,70	0,28	281	8,6
36	Eta Sco	84143	3,3	21,9	19,14	0,28	290	9,0
37	Alpha Men	29271	5,1	10,1	0,70	0,27	298	9,5
38	Lambda Aur	24813	4,7	12,6	1,65	0,27	307	9,9
39	61 Uma	56997	5,3	9,5	0,50	0,27	309	10,3
40	Mu Vir	71957	3,9	18,7	8,39	0,27	310	10,8
41	AX Mic	105090	6,7	3,9	0,01	0,27	312	11,2
42	46 Peg	112447	4,2	16,2	4,56	0,26	314	11,6
43	Sigma Boo	71284	4,5	15,5	3,37	0,26	328	12,1
44	(no name)	49908	6,6	4,9	0,02	0,25	341	12,5
45	Tau6 Eri	17651	4,2	17,9	5,56	0,25	347	13,0
46	36 Oph C	84478	6,3	6,0	0,05	0,25	350	13,5
47	23 Uma	46733	3,7	23,1	15,94	0,25	352	14,0
48	Alpha Cha	40702	4,1	19,5	7,61	0,25	353	14,5
49	(no name)	99825	5,7	8,8	0,26	0,25	360	15,0
50	Eta Crv	61174	4,3	18,2	5,42	0,25	363	15,5
51	Eta Cru	59072	4,1	19,7	7,34	0,24	367	16,0
52	110 Her	92043	4,2	19,1	6,29	0,24	372	16,5
53	V987 Cas	8362	5,6	10,0	0,39	0,24	380	17,1
54	(no name)	47592	4,9	14,9	1,93	0,24	396	17,6
55	Gamma Dor	19893	4,3	20,3	7,04	0,23	398	18,2
56	47 Uma	53721	5,0	14,1	1,49	0,23	399	18,7
57	111 Tau	25278	5,0	14,7	1,74	0,23	403	19,3
58	12 Oph	81300	5,8	9,8	0,31	0,23	404	19,8
59	g Lup	76829	4,6	17,5	3,60	0,23	407	20,4
60	Nu Phe	5862	5,0	15,1	1,86	0,23	411	21,0