SIM ERB REPORT

SIM ERB Membership

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- Dr. William van Altena, Yale University
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The ERB unanimously endorses this Report.

MAJOR CONCLUSIONS

A. The shared baseline concept can undertake nearly all the science programs foreseen in the NRC Decadal reports, is technically feasible, and fits under the NASA-imposed cost cap.

B. The SIM Project still needs the demonstration of picometer technology (MAM-1).

ERB RESPONSE to HEADQUARTERS CHARTER

- *The extent to which the expected scientific performance of these architectures conforms to those foreseen in the NRC Decadal reports.*

  1. Only the original SIM architecture (which is over cost) addresses *all* the science programs foreseen in the NRC Decadal reports.
  2. However, by dropping the requirement for imaging and nulling the Shared Baseline concept fits under the cost cap and can efficiently pursue all the other foreseen science programs.
  3. It is the ERB belief that the science eliminated by changing the requirements can be obtained by other means, for instance by imaging using large ground-based telescopes and interferometers, and/or lower cost space interferometers.
  4. The NRC Decadal reports justified high accuracy space interferometry both for planet finding and mass measurements and for a host of other important astrophysical problems. The McKee/Taylor report stressed that, "A particular attraction of SIM is its dual capability: It enables both narrow-angle astrometry for the detection of planets and wide-angle astrometry for mapping the structure of the Milky Way and other nearby galaxies." [p. 24, repeated on p. 111.]

ERB RESPONSE to HEADQUARTERS CHARTER (CONTINUED)

- *The extent to which SIM will detect planets in the habitable zone in support of the TPF mission.*

  1. When SIM was first proposed the only planetary system known to exist was the Solar System. Now many dozens are known and they have shown us that the extrapolation based on our own system did not prepare us for the wide variety of systems already found by radial velocity techniques. The Shared Baseline concept can discover planetary systems not found by radial velocity techniques and determine the masses for detected planets in all the systems found by both radial velocity and interferometric techniques with an accuracy of 3 Earth masses.
  2. With a five year mission and a $1\,\mu$arcsec, $1\,\sigma$ single measurement error, SIM can detect planets at 10 pc with masses $\geq 3\,\mathcal{M}_{\oplus}$ in orbits and periods comparable to the Earth's.
  3. The outer (long period, i.e. periods > 5 years) planets will be found by non-linear proper motions of the target objects. Translation and rotation of the reference frame will introduce a spurious non-linear proper motion into the target's SIM measured proper motion. Any such spurious proper motion needs to be identified and measured. However, without the Grid and Wide-Angle Astrometry, the search for long period perturbations will be seriously compromised if not impossible (see Appendix A). Among the architectures being considered as alternatives to Classic SIM only the Shared Baseline concept can provide the needed Wide-Angle Astrometry.
  4. If TPF finds orbits for planets with masses lower than the direct detection limit for SIM, a re-analysis of the SIM data using the TPF orbit constraints will often result in a planetary mass or a useful upper limit for the mass.
  5. Because TPF in its imaging mode can discover spectroscopic target planets in a very short time compared to the time needed for the spectroscopy, SIM is not strictly needed to find spectroscopic targets for TPF. However, TPF will not measure planetary masses and SIM is the only mission that can determine the masses of the planets. Without masses, TPF cannot distinguish between rocky planets and gaseous planets of the same brightness and color. **Without SIM TPF becomes PF.**

ERB RESPONSE to HEADQUARTERS CHARTER (CONTINUED)

- *The extent to which the scientific return of the various proposed mission concepts are commensurate with the cost differentials.*

  1. All of the SIM architectures presented to us had nearly the same costs. But as the cost of the satellite is reduced, there is a steep falloff in the scientific performance capabilities of the option. Only the Shared Baseline option meets the cost caps *and* has efficient wide angle capability needed to meet the science aims identified by the NRC Decadal reports.
  2. In fact, the scientific capability of the Shared Baseline option is nearly that of the original (SIM-Classic) configuration which exceeded the cost cap.
  3. The Shared-Baseline concept seems to retain most of the advantages of SIM-Classic, while reducing the complexity, increasing the inferred reliability, and resulting in a substantial cost savings to the project. We have not seen an alternative to the Shared-Baseline concept that can both meet the budget cap and undertake the science programs identified in the NRC Decadal reports.
  4. We are not experts on the costing of space missions, and thus we must accept the costs presented to us at face value. Our evaluation focused on the scientific trade-offs within the cost profiles presented by JPL.

ERB RESPONSE to HEADQUARTERS CHARTER (CONTINUED)

- *The extent to which the implementation approach is sufficiently mature to guarantee the science goals will be met.*

  1. It is important to remember that the design goal of SIM is to achieve $1\,\mu$arcsec angular accuracy for a single measurement. This is equivalent to a angular accuracy of 1/1000 inch at a distance equal to the separation between JPL and NASA Headquarters. The best that has ever been achieved is several orders of magnitude worse than the SIM goal.
  2. As a demonstration of the required technology has not yet occurred, the technology is still not mature. However, the path to the most difficult part, a demonstration of picometer metrology, is now in sight. A critical hardware component is the beam launcher, which must be both thermally stable and optically precise. Two different beam launchers are being developed and both of these seem to be capable of meeting the SIM goal.
  3. The critical milestone will be that of MAM-1. This demonstration of the interferometer at 1/5 scale is scheduled to be held in about 18 months time. If the SIM project meets its milestones successfully passage to phase B is justified.
  4. If in 18 months there is still no convincing technology path showing that SIM could be built with full $1\,\mu$arcsec angular accuracy for a single measurement, alternative designs with reduced goals might be considered.
  5. If the $1\,\mu$arcsec goal for SIM is not achieved, so that only the $3\,\mu$arcsec requirement is reached, then the sensitivity of SIM to planetary masses is also reduced by a factor of three. As massive planets are likely to be gas planets, a degraded SIM may no longer have sufficient sensitivity to detect terrestrial planets. (See Appendices B & C. In this report we are using NASA terminology, ie. we are using the term *requirement* where Tom Fraschetti in Appendix B uses *floor* and *goal* where he uses *requirement*.)

ERB RESPONSE to FIVE KEY QUESTIONS IDENTIFIED BY SIM TEAM

1. *Does SIM fit in the larger framework of other missions and other techniques?*

- SIM is needed for the determination of planetary masses that no other foreseen mission will give.
- SIM will be the first to fly the picometer metrology and nanometer stability that will be needed for future high angular resolution space missions.
- The SIM Shared Baseline architecture concept can – for under the cost cap and at no extra cost – undertake many of the compelling additional scientific programs listed in the NRC Decadal reports.
- We don't really know the type of systems that we are trying to measure with SIM and TPF, since the extrasolar planets that have been detected so far are all in contradiction to our expectations based on our Solar System baseline.

2. *Is SIM feasible from an engineering and technology perspective?*

- The required technology is still not mature until MAM-1 has been demonstrated.
- We think that the technology effort can be successfully completed at a reasonable cost and on a satisfactory time scale, however MAM-1 is a threshold that must be crossed.

3. *Can SIM be built at the proposed cost cap?*

- Without the MAM-1 technical demonstration it is not possible to project a firm cost. Current costs assume that the design can be successfully completed on schedule.
- However, there is now a reassuring agreement between the internal and external cost estimates.

FIVE KEY QUESTIONS (cont.)

4. *Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets?*

- The ERB feels that the capability of the Shared Baseline design is needed if the planetary detection program is to be correctly undertaken.
- The Shared Baseline design is required to establish the Global Grid. This Grid is also needed for many of the non-planetary detection projects.
- There may be some operational cost savings if only the planetary program is mounted. However, such cost savings would be only a very small fraction of the total budget.

5. *Does SIM need global astrometry?*

- In addition to the non-planetary detection projects, the global grid is needed to separate the host star proper motion from accelerated motion induced by long period planets in the system. This is the only way to determine masses for the long period planets (see Appendix A).
- In addition, late type stars have poorly determined masses. If the stellar mass is wrong, the derived planetary mass will also be incorrect. Most of the nearby stars are late type with increasing uncertainties as their mass decreases. The Global Grid is needed so that the masses of such stars can be determined by measuring the SIM parallaxes of binary systems with similar astrophysical characteristics.

ERB ASSESSMENT of the SCIENTIFIC IMPACT of DEGRADED SIM PRECISION

- Unless the single measurement error of SIM in the wide angle mode is worse than 10-11 μarcsec (4 μarcsec mission) accuracy, the impact on wide-angle programs will be modest.

- However, a reduction of the achieved SIM narrow angle single measurement accuracy to the 3 μarcsec requirement increases the lowest planetary mass detectable at 10 parsecs to about $10\mathcal{M}_{\oplus}$ for orbits and periods comparable to the Earth's. The ERB feels that such a loss in measurement accuracy risks losing the terrestrial planets. (See Appendix C for a fuller discussion of this point.)

- As the extrasolar planets that have been detected so far are all in contradiction to our expectations based on our Solar System baseline we don't really know the type of systems that we are trying to measure with SIM and later TPF, thus a loss in astrometric accuracy will result in a loss of knowledge in the diversity in planetary systems.

- To some extent a small loss in position accuracy can be made up by increasing the number of measurements or by using data from other experiments such as TPF or ground radial velocity observations. However this compensation is at the expense of the number and diversity of program targets. (Appendix D lists six SIM-unique planetary programs that will test the satellite's accuracy and efficiency.)

ERB ASSESSMENT of the SCIENTIFIC IMPACT of DEGRADED OPTICAL THROUGHPUT

- Experience with existing ground-based interferometers suggests that the optical throughput of delivered interferometers is typicaly less than predicted. The estimated throughput for the SIM multimirror optical train is based on laboratory reflectivity of silvered mirrors. If the flight versions have only slightly degraded performance, the integration time required for a given magnitude could be substantally increased.

- Depending on the severity of any degraded optical throughput there might be a reduction in the number of targets that can be observed during the mission life and/or some programs will not be possible.

- Of particular concern is whether the throughput of the optical train will be sufficiently high to ensure that the appropriate guide stars needed for planetary detection are bright enough for a tight system lock to be achieved.

ERB ASSESSMENT of the SCIENTIFIC IMPACT
if
SCIENCE PREPARATION FOR SIM IS INADEQUATE

- Of critical importance to the SIM mission is the correct identification of suitable Guide stars, Field stars, and Grid stars. All these stars need to be pre-selected and vetted by ground observations. In particular the Field stars and Grid stars must be stable, ie. the possible motions of their optical centers of gravity are simple enough for them to be used as position standards.

- The number of narrow angle field stars needed for accurate determination of planetary masses depends on the complexity of the motions of the field stars. Selecting too many wastes observing time; too few results in a poorly determined reference frame.

- There will be a temptation to reduce the preflight science preparation. Reduced preparation is a risky gamble and should be resisted.

IMPORTANT POINTS NOTED BY THE ERB

- Shared-baseline SIM enables NASA to accomplish much of the astrophysical research programs of the NRC Report without any additional project construction cost. Only in the operations phase will costs above those needed for measuring planetary masses be incurred.

- While TPF will surely survey all 250 nearby stars for potential extra-solar planet candidates in the imaging mode, the results of that survey will be open to multiple interpretations due to the lack of planetary masses if SIM does not fly.

- The Shared-Baseline concept seems to retain most of the advantages of Classic SIM, while reducing the complexity by almost a factor of two, thus increasing the inferred reliability, and resulting in a substantial cost savings to the project. We have not identified an alternative to the Shared-Baseline concept that could measure terrestrial-like planetary masses that is substantially cheaper.

- The ERB has carefully considered the various proposed architectures for the SIM configuration. As noted above, we strongly endorse the Shared Baseline option for SIM. This option fits within the phase B/C/D cost cap. The other architectures that fit under the cost cap fail to meet all the primary SIM science requirements for extrasolar terrestrial planet detection and result in only minimal cost savings over the Shared Baseline option. Only the Shared Baseline option enables efficient wide angle astrometry, which is necessary for the detection of accelerations. This significantly enhances the scientific viability of the planet detection science, and also permits ancillary astrophysics at no extra satellite costs.

- SIM will demonstrate the feasibility of high-precision metrology in space, a necessary step for TPF and other future NASA missions. In addition, a difficult and expensive component of the SIM effort is the construction of a facility to test SIM at the μarcsec level. We feel that the experience gained by this effort will be of benefit to future NASA missions.

- The SIM project has informed the ERB of how it defines program requirements and goals (see Appendix B). The ERB accepts this statement and believes that they are fully committed to a high accuracy SIM satellite.

ASSESSMENT of the JPL EFFORT

- The ERB was initially skeptical that the Project would be able to meet both the accuracy requirements and the reliability necessary to detect terrestrial planets over the life of the SIM mission.
- We commend the project for their successful efforts to significantly reduce the complexity of SIM. It is our assessment that while SIM is still complex, the reliability risk is low enough and the redundancy is high enough that the loss of the mission from component failure is no longer a major issue.
- Meeting the accuracy goal of SIM has not yet been demonstrated, but a clear path to the required accuracy is seen. The most significant technology hurdle for SIM is the demonstration of stable baseline measurement to 50 picometers. This demonstration is essential to fulfill the $1\,\mu$arcsec accuracy astrometry goal. The importance of meeting this goal cannot be overstated. In particular, a successful demonstration at $1\,\mu$arcsec is needed before the NAR is held. We believe that the SIM group can meet this goal. Therefore the committee enthusiastically endorses SIM once the MAM-1 test bed has successfully shown that the picometer metrology reaches the required accuracy and is robust and reliable.
- JPL has assembled an extraordinarily capable team to confront the extreme challenges of space interferometry. From the top level of science, technology and program management down to the technicians we encountered on the SIM testbed tours, we were extremely impressed with their expertise as well as their determination to meet all SIM requirements. At present no other group in the world combines the JPL space experience with the technical and managerial depth and interferometry heritage of the SIM team.

APPENDIX A

Narrow-Angle Astrometry without the SIM Grid

W. van Altena, 17 April 2001

The assertion has been made that narrow-angle astrometry at an accuracy of 1 μas is not possible without the SIM Grid, a global reference system with an accuracy of 4 μas/star. It is the purpose of this study to investigate that assertion.

Narrow-angle astrometry at an accuracy of 1 μas takes place within a field-of-regard (FoR) with a diameter less than one degree and is required for the measurement of terrestrial size extra-solar planet masses greater than 3 earth masses. To perform these high-accuracy measurements, a total of six reference stars within the FoR are rigidly linked to the Grid to constrain their rotation and scale. Without the SIM Grid, the reference stars will have an unconstrained rotation and scale limited only by the accuracy of their predetermined proper motions. The rotation and scale error introduce a spurious non-linear component into the target's SIM-measured proper motion that could be incorrectly interpreted as an acceleration caused by a long-period planet in orbit around the target star.

The target star's instantaneous position will be measured with respect to its six reference stars within the FoR, and those reference stars would normally be linked to the Grid to constrain their rotation and scale. Let the target star have a position Xo, Yo at time t = 0 and X1, Y1 at time 1, where the two positions are related by the target's proper motion μ and the time interval, t.

$$\text{X1} = (\text{Xo} + \mu x \times t), \text{ and } \text{Y1} = (\text{Yo} + \mu y \times t).$$

The reference stars have positions (xr, yr) with respect to the FoR center and proper-motion errors $(\sigma\mu x, \sigma\mu y)$. The spurious rotation introduced by each reference star is approximately

$$R = (\sigma\mu x \times t)/yr = (\sigma\mu y \times t)/xr.$$

Assuming that the proper motion errors are random and equal in both coordinates, (xr, yr) are randomly distributed over the FoR, and averaging over the nr reference stars, the mean rotation is then:

$$< R >= (\sigma\mu x \times t)/(yr \times \sqrt{nr}),$$

where the proper motion errors and coordinates are the single-coordinate averages.

The spurious scale, (1 + S), is approximately

$$1 + S = 1 + (\sigma\mu x \times t/xr) = 1 + (\sigma\mu y \times t)/yr$$

in x and y respectively. Averaging as above gives

$$1 + < S >= 1 + (\sigma\mu x \times t)/(xr \times \sqrt{nr}),$$

where the spurious rotation and scale change takes place about a center that is defined by the weighted-mean of the reference stars. Since the weights are defined by the product of the distance of an individual reference star from the unknown center times the deviation of the individual reference star proper motion from the true value, we can not *a priori* determine the center; a reasonable guess would be the geometric center of the reference star configuration.

Adopting the above rotation and scale errors, the location of the target star in the spurious frame $X1', Y1'$ after time t is found to be:

$$X1' = [(Xo + \mu x \times t) \times cos\ < R > +(Yo + \mu y \times t) \times sin\ < R >] \times [1 - < S >]$$
$$Y1' = [(Xo + \mu x \times t) \times sin\ < R > +(Yo + \mu y \times t) \times cos\ < R >] \times [1 - < S >].$$

The deviation of this new position from what it would have been without the spurious rotation and scale change, is:

$$dX = X1' - (Xo + \mu x \times t), \text{ and } dY = Y1' - (Yo + \mu y \times t).$$

Noting that the spurious rotation and scale change

$$< R >= (\sigma\mu x \times t)/(yr \times \sqrt{nr}), \text{ and } < S >= (\sigma\mu x \times t)/(xr \times \sqrt{nr})$$

will on average be identical, carrying only the first-order terms in the sine and cosine expansions, and after a bit of algebra the following is obtained:

$$dx = -(X1 - Y1) \times < R > -(X1/2 - Y1) \times R^2 + X1/2 \times R^3)$$
$$dy = -(X1 + Y1) \times < R > -(X1 - Y1/2) \times R^2 + Y1/2 \times R^3)$$

or taking the ensemble average across the field,
$dx = dy = +1.41 \times X1 \times < R > +1.12 \times X1 \times < R >^2 +0.5 \times X1 \times < R >^3$

Two quantities need to be estimated: X1 and xr, i.e. the mean x-coordinate of the target star from the mean reference star center and the mean distance of the reference stars from their center. These both depend on the diameter of the FoR.

The diameter of the FoR for narrow-angle astrometry is given as 1.0 degrees. However, that will be inadequate if Hipparcos stars are to be used as reference stars, since a FoR diameter of 1.74 degrees is necessary on average to obtain six Hipparcos reference stars. Adopting 1.74 as the diameter of the FoR, leads to $< xr > \sim 0.62$ degrees. We should really be forming the average of $< 1/xr >$, but there is little difference here, since $< 1/xr > \sim 0.59$ degrees.

The mean value of X1 is more difficult to estimate. It is possible to go through all of the 250 candidate stars and find the six nearest Hipparcos stars in each case and evaluate the actual situation. Instead, I have used a range of X1, running from 0 to 1000 arcsec, which covers the possible range. A SIM time baseline of 5 years has been adopted.

Type of Ref. Star	Field of Regard	Ref. St. $\sigma(\mu)$	dx (X1=10")	dx (X1=110")	dx (X1=410")
Hipparcos	1.74 deg.	1 mas/yr	13 μ as	143 μ as	534 μ as
FAME	1.74	50 μ as/yr	1	7	27
FAME	1.00	50 μ as/yr	1	12	46
Random	1.74	17 mas/yr	222	2437	9084
SIM Grid	15	4 μ as/yr	0.006	0.066	0.248

To get a feel for what value of X1 would be reasonable for the FoR = 1.74 deg., I adopt a corresponding rms radius of FoR/4 and divide by the square root of six - this will surely give an X1 that is too small, since the reference star distribution will be uniform, not Gaussian. This leads to X1$\sim$640 arcsec, which is beyond the above table, which shows clearly that the only solution that keeps the spurious non-linear motion under the SIM measuring accuracy of 1 μ is the solution with the SIM Grid. A solution using FAME reference stars is possible, but it requires that the six reference stars be selected so carefully that their mean position is within 10 arcsec of the target star; this is not practical. It is not possible either for many of the nearby potential targets, since their large proper motions would soon carry them beyond the 10 arcsec limit.

Conclusion: 1 μ as narrow-angle astrometry designed to determine the masses of extra-solar planets requires the existence of the SIM Grid if spurious accelerations mimicking long-period planets are to be avoided.

APPENDIX B
EMAIL RECEIVED FROM THE SIM PROJECT

Hi Joe,

With all the confusion over what a goal is vs a requirement vs the floor, I thought I would define, in writing, how the SIM Project defines the terms. At the Project level we have only requirements and a floor. For planets our requirement is 1 microarcsec. The Project generates what are called Level 2 requirements, which is what is flown down to the design team. These Level 2 requirements specify 1 microarcsec as the narrow angle performance requirement. All lower level requirements including the SIM error budget reflect this 1 microarcsec requirement. This is what we are designing to, and this is what we intend to achieve.

Our present plan is to achieve at least 3 microarcsec on the MAM-1 test bed by June of 2002, and we will achieve 1 microarcsec by August 2003. This is our requirement for MAM-1, and this is what we plan to achieve.

Now about the floor. Every project is required to have a science floor. This is the minimum level of performance below which the project is cancelled. For SIM narrow angle science, that floor is 3 microarcsec.

The SIM team is dedicated to meeting the 1 microarcsec requirement, and I assure you our science team will insure we do. We will demonstrate this level of performance at least a year before NAR, and well before we start spending serious money.

I hope this explanation helps alleviate your fears about how SIM will perform from a planet science standpoint. Please feel free to forward this message to your team. If anyone has questions, please feel free to contact me. You have my email. My phone number is 818-354-6677.

Tom

APPENDIX C
ON THE SEARCH FOR TERRESTRIAL PLANETS

The ERB notes that the February 25, 2000 *Final Report report of the Space Interferometry Mission Science Working Group* recomends in Section 6.1 (p. 20) that the narrow angle science requirements have a *goal* of 0.15 μ arcsec and a recomended Requirement of 0.5 μ arcsec and a Floor of 3 μ arcsec. On page 23 these requirements are relaxed somewhat for the search for Earth-sized planets orbiting around Solar-type stars. That Goal was set at 0.3 μ arcsec and the Recomendation was for 1.0 μ arcsec. They state, "The instrument requirements are easier for the Recomendation than for the Goal because the target list is smaller and therefore the targets can be closer." They continue; "There is no Science Floor specified. The search for Earth-sized planets is extremely demanding and may prove to be beyond the capability of SIM."

Planetary atmospheres can be formed both by accretion from the protoplanetary nebula and from outgasing from the early planet interior. If the planetary mass is very low, the primitive atmosphere will escape. Even though the necessary studies of the formation of atmospheres on Earth-mass planets are lacking, the presence of Uranus and Neptune in our solar system suggests that by about 10 Earth masses all planets will retain sufficient gas to form a dense, life-hostile atmosphere. And even Earth-mass planets, such as Venus, can have hostile atmospheres. In fact, at the surface of Venus the atmosphere is so dense that its viscosity is about the same as water.

Thus, the ERB is not only concerned about the ability of SIM to find Earth-sized planets but also to find *terrestrial* planets. The comparison with our own solar system suggests that there may only be a narrow range of planetary masses with sufficient gravity to retain some atmosphere but not so much gravity that a dense atmosphere, hostile to life, is retained.

It is clear that if a major goal of SIM is to locate planets that might harbor life forms, the higher the astrometric precision of the satellite, the better. The difference between 1 and 3 μ arcsec may not seem like much but it may make all the difference when the aim is to find planets with life-friendly conditions.

However, even if SIM only achieves 3 μ arcsec in orbit and detects no terrestrial planets, it will still be an important tool for characterizing planetary systems.

APPENDIX D
A LIST OF PLANETARY PROGRAMS UNIQUE TO SIM

(Courtesy of Peter Bodenheimer)

Thanks for the ERB draft. As sort of a summary, here is what I think SIM can do that is unique (if properly designed) in the area of planet detection

1. Determine the diversity and architecture of a variety of planetary systems.
2. Determine unambiguous masses.
3. Push the detectability threshhold for planets down by an order of magnitude in mass as compared with radial velocity surveys (that is to around 5 earth masses).
4. Find solar system analogs with respect to giant planets, that is, systems with Jupiter-Saturn mass planets at or beyond 5 AU with no giant planets inside 5 AU.
5. Find planets around young stars (T Tauri stars as well as young main sequence stars) which can't be touched by the radial velocity technique because of too much stellar activity.
6. Identify life-bearing candidates, but only in a very preliminary way, with emphasis on the word 'candidate', which would require extensive further study.

Cheers, Peter