The Space Interferometry Mission:

Taking the Measure of the Universe

Final Report
of the
Space Interferometry Mission Science Working Group

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* resigned 1997   ** resigned 1998

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1 Executive Summary

1.1 Optical Interferometry and the Millennium

With the Millennium comes a new age in space, the introduction of the big optical interferometers. The goals, near and long term, are remarkable: searching for nearby exoplanets and characterizing their atmospheres, characterizing the size, shape and dark matter content of our Galaxy, pinning down the ages of the oldest stars. The list goes on.

But optical astronomical interferometry is not for the amateur. Invented more than a century ago, it is only beginning to realize its potential from the ground, having been stymied by the atmosphere for decades. Even without the rather remarkable technologies required to compensate for atmospheric effects, the technique is not easily implemented on the ground, let alone unattended in space. Add to this the desire to take advantage of the access to the sky for angular measurement over both large and small angles, and you have a daunting challenge.

The answer is to advance the technique in steps. The steps must be aggressive, providing answers to scientific questions that justify the effort while demonstrating technologies in sizable increments. But the steps cannot be so large as to demand technology development on the scale that would drive the cost beyond reason and the credibility of the missions beyond realistic expectation. And so we have the Space Interferometry Mission.

SIM fits well the requirements for being an ideal space mission. It promises a remarkable return in science, affecting and furthering just about every aspect of Astronomy. And the technology associated with optical interferometry in space, even for this first step, carries us way beyond current practice. In the end, all this technology must become "off the shelf" reliable if we are to go on with the really big interferometers, whether they be for searching for Earths around other stars or for allowing us to build truly large imaging devices in space. SIM is the logical first step of all of this.

1.2 Astrometric Interferometry

SIM operates in three major modes: global, or wide-angle, astrometry, narrow-angle astrometry, and synthesis imaging and nulling-imaging, with the great majority of the science coming from the astrometry modes. Astrometry, the science of making precise position measurements, is astronomy at its most fundamental. Yet, major advances in fundamental measurements can be extraordinarily scientifically rewarding. In this case what is sought are the changes in position signifying, by motions reflex to the Earth's motion around the Sun, a certain distance, or reflecting the large scale motions found in systems like the Galaxy and even the randomness of our flight through the Universe, or suggesting the presence of an unseen, planetary mass companion to a nearby star.

Over the decades, astronomers have found ways to look at these problems to limited extents - we know what kinds of questions to ask and the magnitude of the scientific return that precision astrometric measurements will provide. We can define the measurement requirements with some accuracy. Still, the breadth of the impact of this one instrument is astonishing.

Planetary and Substellar Companions

Probably the most visible and publicized questions that SIM will answer involve the extent to which stars have substellar ($M \lesssim 0.08\,M_\odot$) and planetary ($M \lesssim 10 M_J$) mass companions and systems of such companions. This area came to electrifying life in late 1995 with the announcement by Mayor and Queloz (1995) of the discovery of a Jupiter mass companion orbiting 51 Peg, a nearby solar type star. Since then fully a dozen such detections have been reported.

The technique used, detection of small, periodic Doppler velocity variations, gives a lower limit to the mass of the companion owing to projection effects, a limitation not inherent to SIM's measurements. Further, astrometric measurements provide a substantially different discovery space than Doppler variations. This can be seen in Fig. 1 where the limit of a significant detection from velocity variations is compared to the corresponding limits for SIM and two ground based astrometric efforts (companions whose mass and separation would place them above the lines would probably be detected by the respective instrument).

Even with optimistic estimates for improvement in velocity detection, the only instrument with the potential to detect an earth in the zone of habitability around the nearest stars in the next decade is SIM. SIM will probe a significant number of stars for massive terrestrial planets in the 1–3 AU zone and will sweep for systems of gas giant components around solar type stars within 10 pc. The field of planetary system formation will finally be put on a firm empirical footing.

Stellar Astrophysics

SIM will revolutionize the traditional areas of stellar structure and stellar evolution. It will flesh out the mass-luminosity relation to the hydrogen burning limit. At the other extreme, the brightest, but rarest stars will have accurate distances and luminosities for the first time. The contact between observation and theory for Cepheid pulsation will be improved a hundredfold.

Of particular significance will be the accurate, $\lesssim$ 5%, distances to a selection of globular clusters. Distance uncertainties dominate the calibration of their luminosities and turn off masses and in turn their ages. The improved distances should reduce the age uncertainties by a factor of two, down to about a half Gyr. This will substantially sharpen the comparison between the age of the oldest stars we know and the age of the Universe as estimated from the Hubble expansion.

The Galaxy

There is probably no more natural a fit between SIM capabilities and an object of interest than the Galaxy. At its target capabilities, SIM will determine distances accurate to 10% to objects that are twice the solar distance from the center *on the opposite side of the Galaxy.* The situation is illustrated in Fig. 2 (with M101 standing in for the Galaxy). Any object in our Galaxy meeting SIM's magnitude limit (V = 20) can have its distance measured to $10\,\sigma$. Every classic Galactic structure parameter will be determined: R_0, the distance from the Sun to the center; V_0, the Sun's velocity around the center; V(R), the rotation velocity law and Φ(z), the potential above the plane.

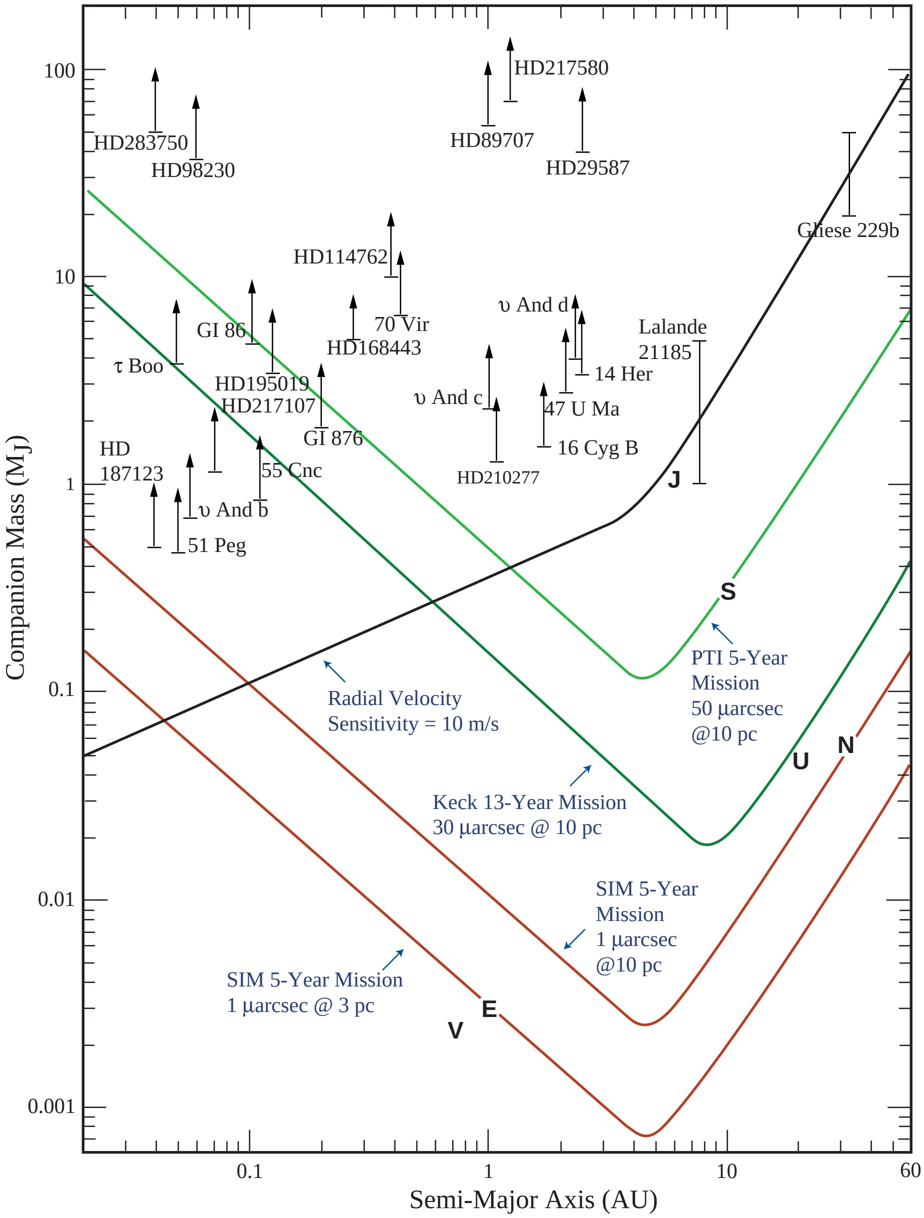

Figure 1: Parameter space for detecting planets and substellar companions by radial velocity variations and with several astrometric instruments. Shown also are the currently known detections with minimum masses below $80M_J$ including the three components of the υ And system. A solar mass primary is assumed. Courtesy Rudi Danner: JPL

Our picture of the Galaxy has been undergoing remarkable change of late. Searle and Zinn (1978) have shown that galaxies probably grow by cannibalizing small neighbors, a view remarkably confirmed by the discovery of the Sagittarius dwarf irregular galaxy plunging through the opposite side of the Galaxy (Ibata, Gilmore & Irwin 1994). This picture implies that the Galaxy may be threaded with tidal debris trails and may not resemble a relaxed disk of stars at all. Interestingly, accurate measurement of the kinematics of these trails, particularly those from Sagittarius, may give the best indication yet of the

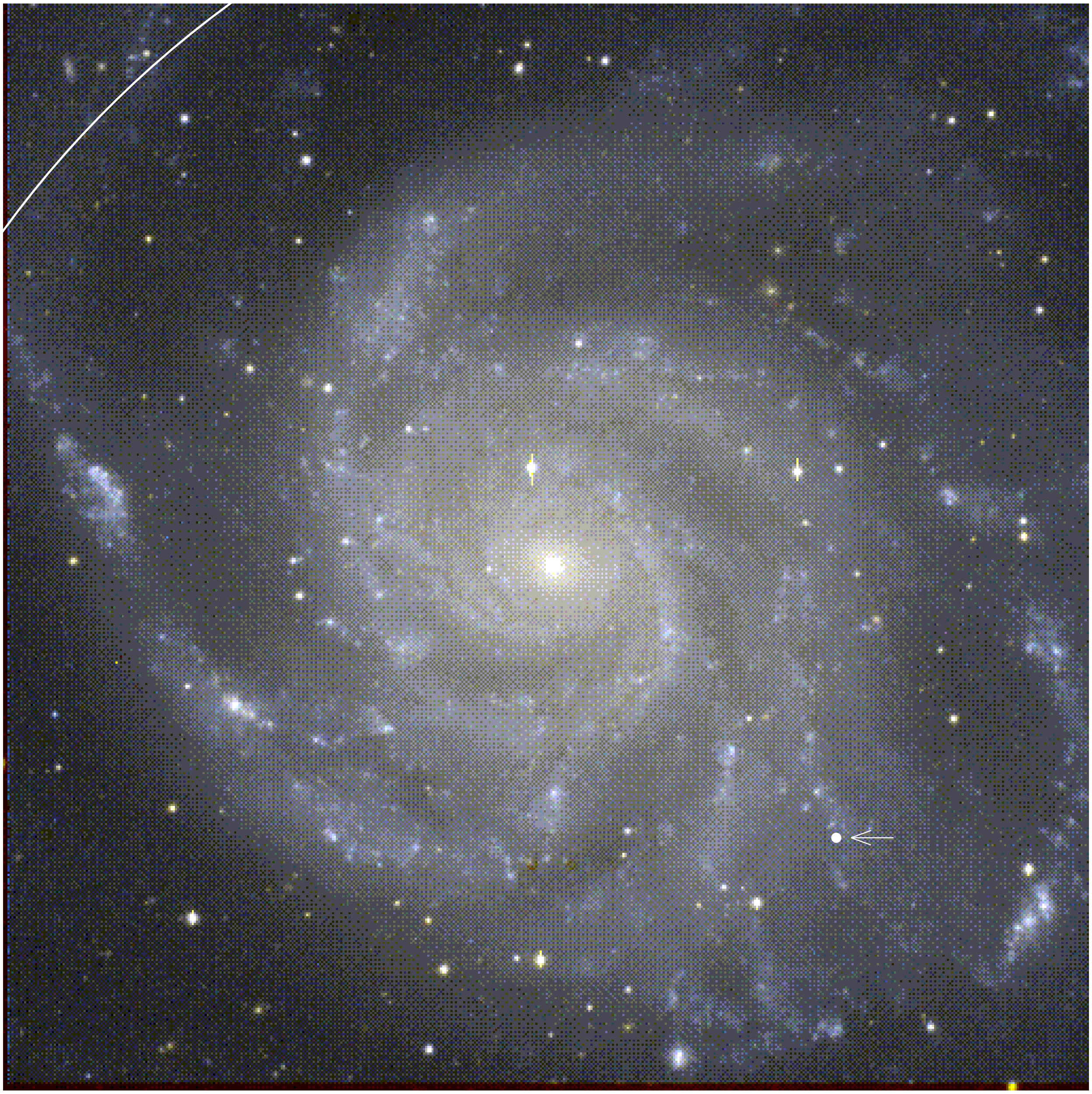

Figure 2: Illustrating the coverage for distance determinations, with M101 standing in for the Galaxy. The size of the small dot to the lower right, roughly 8 kpc from the center corresponding to the Sun's position in the Galaxy, indicates the 10% accuracy region of the HIPPARCOS mission. For SIM we show the 8% accuracy circle centered on the dot, a segment of which is visible in the upper left corner. The 10% circle would be entirely outside the boundaries of this image.

mass and figure of the Galaxy.

In the meantime Blitz and Spergel (1991) have confirmed that the Galaxy has a massive central bar. The parameters of the bar are known only in outline but can easily be measured by SIM.

Finally, the question of the amount and distribution of dark matter in the Galaxy remains very poorly constrained. Several lines of evidence argue that a massive halo must be essentially spherical. Direct measurement of the mass of that halo requires measuring the motions of objects that orbit the Galaxy at galacto-centric distances of 100 – 200 kpc. These are the distant globular clusters and the dwarf satellite galaxies. The relevant proper motions are well within SIM's reach.

The question of dark matter can also be attacked locally. Over the past few years international collaborations going by acronyms like MACHO and OGLE have been monitoring dense fields of stars looking for gravitational lensing by faint foreground objects. What is measured, the light amplification and event duration, are complicated functions of the lenser mass, the distances of the two objects and their relative velocities. Statistical arguments are required to estimate the mass of foreground objects involved. Independently, Paczyński (1998) and Boden et al. (1998) have pointed out that even though SIM won't see the foreground objects it can still determine their parallaxes, and hence masses, directly. This will determine directly whether these objects can account for the missing mass.

The Universe

SIM will also make fundamental measurements that will directly impact our understanding of Cosmology. For example, a critical parameter characterizing the expansion is the size of the residual random motions, the "temperature" of the Hubble flow. Radial velocity measurements do not easily yield this since they are superimposed on the expansion. SIM's proper motions will yield estimates of tangential velocities that will measure the randomness after only minimal corrections for local infall.

One of the major accomplishments of the Hubble Space Telescope has been to measure Cepheid based distances to a number of distant galaxies, thereby determining the Hubble constant with unprecedented confidence. The remaining step is to firm up the zero point calibration of the Cepheid Period–Luminosity relation. By using "Rotational Parallaxes" (Fig.3), we will be able to determine the distance to the M31 (Andromeda) and M33 (Triangulum) galaxies, and possibly a few others, to a few percent. This would bypass the myriad of intermediate steps, providing accurate distances directly for systems with huge populations of Cepheids. In so doing, SIM would improve our estimate of the age of the Universe, sharpening further the comparison with the ages of the globular clusters, described above.

1.3 Nulling and Imaging

Finally, SIM will demonstrate the technique of synthesis imaging in space. This technique is well understood in radio astronomy circles and is just being implemented with ground based optical interferometers. SIM offers two unusual twists on the technique. First, in order to provide the stability required for the astrometric science, SIM will have knowledge of its configuration far more accurately that is common in typical interferometers. This will allow recovery of high dynamic range in the reduced images. Potential targets include mapping the rotation fields around black holes in the centers of nearby active galactic nuclei at almost an order of magnitude better resolution than currently available.

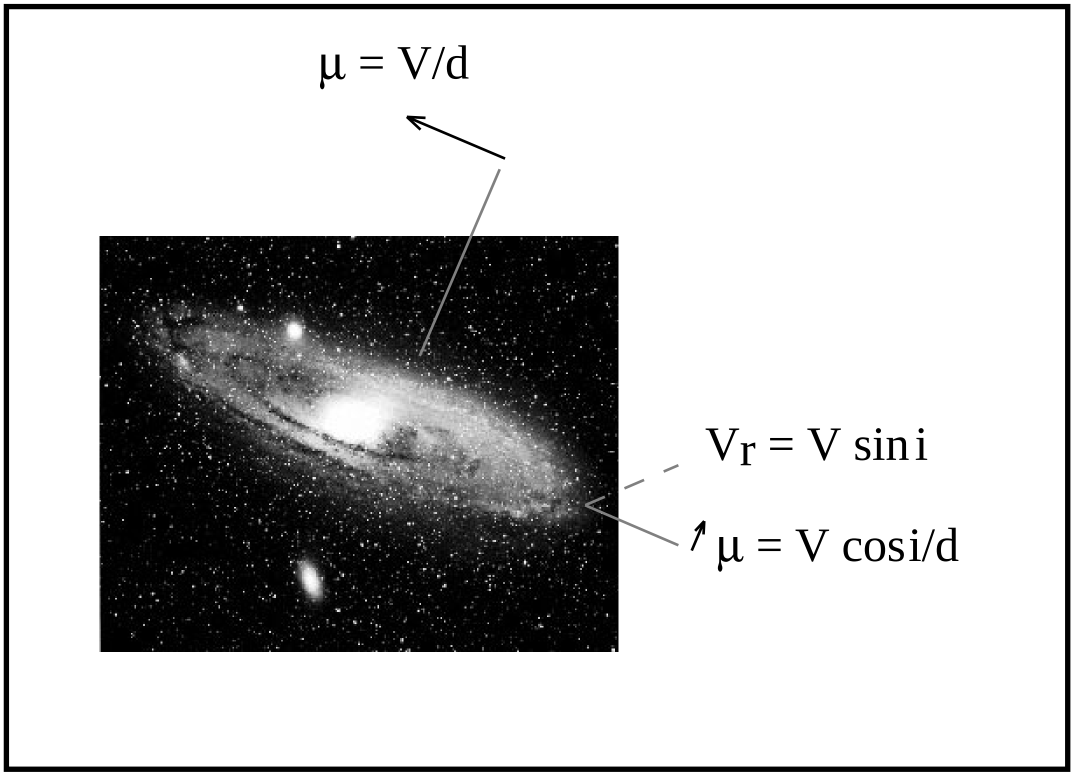

Figure 3: M31, showing the proper motion and radial velocity measurements needed to solve for the distance, the “Rotational Parallax”.

Secondly, in order to test the technology necessary for deep, broad band nulling, SIM will provide a synthesis nulling-imaging capability (without retaining phase information). A particularly interesting application will be to look for dust “debris” disks around nearby stars to substantially fainter levels that can be imaged at present. The two or three examples currently known (*i.e.*, β Pic, Smith and Terrile 1984, see § 7) show evidence of zones free of material in the disks, possibly because of the formation of planets. SIM should be able to probe for such structures in disks another factor of $10 - 100$ fainter.

1.4 Operation and Interaction with the Community

SIM is an unusual instrument. As we will describe, the mission requires that a special group of stars, the “Grid” be measured over and over until their relative positions are known exquisitely. Scientific targets will be measured relative to the Grid (wide-angle) or at least require the Grid as a fundamental part of the measurement (narrow-angle).

This being the case, much of the science will not be available until the end of the mission. However, in order to shake down data reduction and provide the most demanding check on the operation of the instrument, a mid-mission Grid reduction is called for, which will allow some science to be accomplished and released.

This dependence on a Grid solution is so fundamental to the proper extraction of scientific results that for most of the science and particularly for the wide-angle astrometry there will be no useful preliminary measurements before these full-up Grid solutions are completed. As a result, a one year proprietary period for data analysis has been recommended for the mission. This is described in more detail in § 4.

1.5 The SIM Technology Legacy

The current NASA time-line has SIM flying in 2006. SIM is a critical technology precursor to the Terrestrial Planet Finder mission, tentatively scheduled early in the next decade. Further, technology developed for SIM, particularly the precision control systems, will find their way into NGST which is scheduled for launch in 2007. Beyond simple technology, important experience on how to operate a complicated interferometer in space will accumulate. SIM is a step on the critical paths of the next generation of NASA's major missions, a step that will provide enormous technical, scientific and ultimately philosophical return.

When it flies, SIM will truly "Take the Measure of the Universe".

2 Introduction: Taking the Measure of the Universe

2.1 Global Astrometry

Astrometry, for many decades considered a necessity in Astronomy but not an area one would recommend for graduate study, is undergoing a renaissance, if not a revolution. Application of modern detectors and availability of cheap, high speed computing has enabled large scale deep surveys with high positional accuracy. Space has allowed freedom from the loss of astrometric stability over large angles due to the atmosphere.

Starting with Irwin Shapiro in the mid 1970's, a series of suggestions about how to inexpensively exploit space for astrometric purposes have been put forward (Reasenberg & Shapiro, 1979, Perryman 1986, Gershman, Rayman & Shao 1991, Lindegren, et al. 1994, among others). The success of the HIPPARCOS mission in the early 1990s served as a dramatic demonstration of the potential of "Global Astrometry", a technique enabled by access to most of the sky at any time, that allowed accurate positions and motions to be measured and *absolute* parallaxes to be derived. (The residual uncertainty of a uniform rotation was minimized by tying the positions to an extragalactic reference frame).

It was quickly clear that the potential of this technique had only been glimpsed. Proposals to improve HIPPARCOS's nominal 1 mas accuracy down to $V = 9$ projected accuracies of a few microarcseconds at magnitudes of $V = 15 - 20$. In 1996, recognizing this, the additional potential of these instruments in detecting planets around nearby stars and that interferometry would play an increasingly important role in future space missions, NASA selected Shao's Orbiting Stellar Interferometer (OSI) proposal for its first major interferometry mission, the Space Interferometry Mission (SIM). (The history of that selection process can be found in the Final Report of the Space Interferometry Science Working Group 1996, and is briefly summarized in § 3).

2.2 The SIM Concept

The basic design, an artist's conception of which is on the cover, is for three, roughly collinear, nominally 10 m baselength, Michelson interferometers to operate simultaneously. At any time, two of the interferometers observe bright stars to provide knowledge of changes in orientation during the measurement. The third, the science interferometer, measures angles projected along the direction of the baseline between objects in a nominal 15° diameter "Field of Regard" (FOR). A second observation with the baseline orientation at roughly 90° completes a set of local position measurements.

A few objects in every FOR are members of the "Grid". The Grid is observed in separate campaigns of overlapping FORs designed to allow their positions to be measured with respect to every other Grid member over the sky. This set of objects provides the Global Astrometry solution. Science object positions are measured with respect to local Grid members.

Errors in the measurement process come from several sources. A major error source is associated with mirror motion as the science interferometer moves from object to object in the FOR. This source can be substantially minimized if mirror motions are limited to, say, 1°. In this "narrow-angle" mode (mirror excursions over a sizable fraction of the FOR are "wide-angle" mode) significant gains in the accuracy of relative position measurement are expected. It is this additional accuracy that enables the exoplanet search.

In its simplest form SIM will provide fixed baseline synthesis imaging capabilities. This can provide the equivalent resolution of a 10 meter aperture on fields known to be particularly simple (*i.e.* a few point sources). Configurations have been proposed that would provide most or all the baseline spacings that would be required for essentially full synthesis imaging of arbitrary fields. The fate of these proposals is not yet decided.

Finally, as part of its technology pathfinder role, SIM will demonstrate two mirror, on axis nulling to at least a factor of 10^4 over at least a 20% bandpass. This is in essence just another way of measuring components of the complex Fourier Transform of the image. However, giving up measurement of the Fourier phase thereby taking advantage of the low noise environment of a nulling measurement, one can attack problems of detecting low brightness objects in the vicinity of bright point sources.

2.3 The SIMSWG Contribution

With any major mission it is customary for NASA to constitute a committee of scientists with expertise in the various relevant areas to advise the Agency on the "scientific rational and requirements" of the mission. Such is the relationship between the SIM Science Working Group (SIMSWG) and SIM. This document, the Final Report of the SIMSWG, constitutes that advice.

In the sections that follow we describe the history of that process and the committee's charter (§3) and the context SIM finds itself in terms of recent and current developments in Space Interferometry (§10). We make recommendations on how SIM should interact with the public and the scientific community and on the general timing of data reduction and data releases (§4). But most importantly, we provide the scientific rational and requirements that would make for a successful mission (§5 – §9). Here we outline the critical areas and questions that SIM can address and answer. These areas and questions are not claimed to be exhaustive. However, we find them both so compelling and yet within SIMs potential to address, that to not address them would call into question the viability of the mission.

In this particular grouping of sections, which have separately been the focus of most of the committee's efforts and have come to be known as the the "Science Requirements Document" (SRD), we establish the current state and desiderata of a dozen critical scientific topics. We deduce the types of measurements that SIM must make and the accuracy required to resolve the questions posed to various level of refinement. These quantitative requirements are then combined to characterize the performance needed from SIM at the different levels. In particular, §8 summarizes the minimum overall performance profile, the "Floor", that would constitute a scientifically viable, cost effective mission of this size.

3 The History of the Working Group

3.1 SIM, AIM and ExNPS

The SIMSWG was constituted in the Summer of 1996 by the Origins Division of NASA's Office for Space Sciences to provide scientific guidance for the Space Interferometry Mission (SIM). The committee succeeded the Space Interferometry Science Working Group (SISWG) which stood down that Spring after assisting NASA in identifying the appropriate architecture for the Mission. In turn, both committees were the outgrowth of the National Research Council decadal report (Bahcall 1991) that strongly recommended the US pursue space astrometry in the form of the Astrometric Interferometry Mission (AIM).

In parallel, NASA's (at that time) SL - planetary - division had spent the better part of a decade considering how to identify planets orbiting other stars. This effort culminated when NASA Administrator, Dan Goldin, challenged the Astronomical community not just to find Jupiters, but to find Earths around other stars. In fact, he insisted the goal should be to image those Earths. The community responded by setting out the Exploration of Neighboring Planetary Systems roadmap (ExNPS, 1996). As their last act before standing down the SISWG certified to NASA that the OSI architecture proposed by JPL could perform AIM science as provided by the Bahcall report and could act as the technology testbed for the instrument conceptualized in the ExNPS roadmap (now called "Terrestrial Planet Finder" - TPF). The Mission combining both the science and technology goals was renamed SIM. A detailed history of the SISWG and the convergence of the AIM and ExNPS goals and processes can be found in the Final Report of the SISWG (1996).

3.2 The SIMSWG

The inaugural meeting of the SIMSWG was held in Pasadena (IPAC) September 13/14, 1996. Tom Livermore was introduced as SIM's pre-project manager and Steve Unwin as the Deputy Mission Scientist (albeit acting much as Mission Scientist given the many demands on Mike Shao). No minutes are available for that meeting. The main business was the introduction and discussion of the SIMSWG charter and of a draft Science Requirements Document.

The Charter

The SIMSWG charter agreed to earlier by the co-chairs and Origins director Ed Weiler is as follows:

> *The Space Interferometry Mission Science Working Group (SIMSWG) is chartered to advise the NASA HQ Program Scientist and Program Manager, the JPL SIM Project Manager and Project Scientist, and the project in general, on aspects of the Phase A study of the mission which are of relevance to the scientific community.*
>
> *In particular, the SIMSWG is chartered:*

- *To develop and to refine the science rationale and requirements for the first astronomical interferometry mission in space. These requirements will reflect the Bahcall Report recommendations, the work of the Space Interferometry Science Working Group (SISWG), and other advice to NASA.*
- *To comment upon the impact on the science program of critical and enhancing technologies for the Space Interferometry Mission (SIM) and particularly to consider the impact on the science program from SIM's role as the technology precursor for the Terrestrial Planet Finder instrument. This will include confirmation that the adopted architecture(s) will achieve the program's science goals.*
- *To evaluate operating modes and observing capabilities of SIM, including the proposed data analysis effort, possible guest observer programs, and to generally represent the interests of the scientific community in the productive operation of the mission.*

4/Sep/1996

The Science Requirements Document

As emphasized in the charter, the primary responsibility of the Working Group was to devise an optimal scientific rational for the Mission and identify what is required of the instrument for it to meet those goals. At the inaugural meeting Unwin's draft SRD was circulated and briefly discussed. Primarily taken from the SISWG's Strawman Science Proposal (1996, section 4) it was deemed that the sections needed substantial study, both to better characterize the detailed demands on the instrument and to make sure that the document identified topics that included all major instrument drivers. The common element of all following SIMSWG meetings was the continuing effort to hone this aspect of the document.

An unexpected aspect of the SRD was introduced at that meeting: rather than be just advisory to Headquarters, the Project proposed to make the document the direct source of the instrument drivers that accrue to the required scientific performance. The Project proposed that a sign-off page be provided with the signatures of principals of both the Project and the SIMSWG to be executed on adoption. Although NASA Headquarters and the Project have since backed away from that model - the document will be advisory as indicated in the charter - most of the SIMSWG's interactions with the Project took place assuming the more direct model. (In retrospect, this was beneficial, with exchanges of views more immediate and misunderstandings less prevalent than one might otherwise expect).

3.3 The Floor Specification

The second SIMSWG meeting took place in Baltimore on Dec 9/10, 1996 at the invitation of the Space Telescope Science Institute. The minutes of this and subsequent meetings are archived on the Stony Brook SIMSWG site:

http://www.astro.sunysb.edu/simswg/index.html and on the JPL SIMSWG page. In addition to discussing the expanded SRD the committee drafted (in what turned out to be nearly final form) an extremely critical section, the so-called "Floor" requirements. As defined in detail at the beginning of the SRD sections, these are specifications of instrument performance which, if they could not be met, would constitute a critical, mission threatening, failure. As the "design-to" specifications continued to be somewhat ill defined as the SRD was thrashed out, the Floor specifications provided the Project a stable statement of the absolutely minimum capabilities required, a critical point of reference for the Project during this period.

3.4 Entering Phase A, A Son Emerges

SIMSWG-3 took place on October 27/28, 1998, in Pasadena's Hilton hotel, immediately following the first SIM Workshop. The news was mixed. Chris Jones was introduced as the replacement to Tom Livermore in anticipation of SIM entering Phase A, the letter announcing the start of Phase A was received during the meeting, and the SIMSWG was informed of the formation of a parallel design study by the Project, dubbed "Son-of-SIM" (SOS). The last, following from an innovative suggestion by Stu Shaklan, was advanced as a way to materially reduce the number of moving parts within the basic OSI architecture. A serious design study had been initiated within the Project. The decision on which design to pursue for SIM was to be taken in the December – February window.

The SOS issue proved much more difficult than that. SIMTAC (Technical Advisory Committee) meetings in December and February (attended by representatives of the SIMSWG) concluded that SOS was the preferred architecture. The fourth SIMSWG meeting, held April 23/24, 1998, at the Embassy Suites in Arcadia CA, was dominated by the "SIM-Classic" versus SOS presentations and discussion. Although the SIMSWG did not oppose the decision, it expressed serious concern that the projected narrow-angle error budget did not meet the emerging SRD recommendations. Concern was also expressed about a number of other critical components where compliance with extremely demanding specifications could not be confirmed. Headquarters was formally notified of the SIMSWG's conclusions. (The Project later informed the SIMSWG that the decision in favor of SOS had been rescinded until such time as those and related issues could be clarified).

It was not until early Fall of 1999 that the Project concluded that, while there were no known faults with the SOS design, a number of serious technology questions remained outstanding, questions that could not be answered on the required timescales. Time had run out. Tom Fraschetti, replacing Chris Jones as Project Manager, proposed that the Project would proceed with the Classic design. Following an email discussion, the SIMSWG concurred.

Two other SIMSWG meetings were held in the meantime, SIMSWG-5 hosted by CalTech on July 27/28, 1998 and SIMSWG-6, hosted by the University of Arizona on February 11/12, 1999. The latter in particular included a productive discussion of what the SIMSWG dubbed "Operating Mode" issues (described in detail in § 4) and a notably divisive discussion of the status of Project Science Team members in the coming Science Team/Key Project Announcement of Opportunity. In the end, NASA Headquarters took the latter issue under advisement. To date no formal announcement has been made of the policy to be adopted.

3.5 No Level 1 Document

In the year that followed SIMSWG-6, requests for advice from Headquarters and the Project were handled informally or through email exchanges and subsequent email votes. Notable among the latter was a proposal to adopt a "Level 1" specification (the basic capabilities that JPL would agree to provide in the launched instrument) that took over the SRD requirements on narrow-angle performance but retreated an order of magnitude on the wide-angle specification (to the minimum levels called out a decade earlier in the Bahcall Report 1991). After considerable, spirited discussion by email and a unanimous agreement that this could not be allowed, a meeting with the Origins Director and others from Headquarters saw the proposal withdrawn. The official reason for that action was that Level 1 documents or their equivalent were not due until the end of Phase B of mission development.

The Announcement of Opportunity for Science Team Membership and Key Project Proposals was released in late February, 2000. Science Teams replace SWGs at the beginning of Phase B in Mission development and there is a period of official silence during the proposal process. The SIMSWG officially stood down with the appearance of the AO.

4 SIM Operating Mode and Data Issues

The SIMSWG charter asked the committee for certain advice and guidance. One of the areas had to do with how the mission interacts with the community on a number of issues (cf. § 3.2, specifically the third item).

Of the many issues that came generally under this heading, the SIMSWG considered those that seemed the most immediate and made recommendations on what policy should be implemented. In a couple cases it was concluded that the to-be-appointed Science Team and/or the Interferometry Science Center (ISC) staff would be in a better position to suggest policy or how to implement a policy, and the committee so recommended.

The specific issues considered and for which recommendations were agreed on included:

- The unusual nature of the preparatory scientific effort needed for SIM and the correspondingly unusual Funding Profile that should be considered.
- The sensitive issue of Data Rights and Proprietary Periods.
- Whether and when to have an Intermediate Data Reduction during the mission.
- And to what extent there should be Redundancy in the Data Reduction effort.

The recommendations sent NASA follow:

4.1 SIM Science Funding Profile

Nearly all the science areas identified in the Science Requirements Document will see a rapid ramp up in activity during the Preparatory Science phase. Many, although by no means all, will see reduced activities during the main mission, with a return to a higher activity level shortly before release of data and for a couple years thereafter. This will require some departure from the normal NASA mission funding profile. (A notable exception to this is imaging science, which will probably experience a slower ramp but will enable a significant guest observer with corresponding costs during the main mission phase).

First, it is imperative that there be a strong ramp up to full funding in the first year or two upon the designation of a Key Project. This is required since almost without exception the preparatory work will involve immediate instigation of extensive observing programs, data reduction and follow-up observations, for input catalog preparation. This up-front funding is not traditional, but recruitment of postdocs and graduate assistants in a timely manner makes it imperative.

Second, some, but definitely not all, of the science areas likely to be accorded Key Project status, will experience a decrease in project related activity shortly following launch. That will often be accompanied by a decrease in required funding, typically with postdocs going on to other jobs and graduate students graduating. In these cases, funding must be maintained at the level necessary to maintain the viability of the main members of the Key Project. Justifications for these *expenditures include the ability to react with reasonable speed to unexpected requests from the Project and particularly the Interferometry Science Center, the expectation that an intermediate reduction at launch plus 2.5 years will lead to a full shakeout of reduction codes and examination of the SIM data products at all levels, and the resulting expectation that preparations will begin for an extended mission.*

Finally, a return to peak funding should be expected shortly before the end of the nominal 5 year mission in anticipation of achieving the missions full scientific promise. If an extended mission is involved, additional needs will need to be meet.

The SIMSWG recommends to NASA that appropriate plans be made to accommodate these unusual funding profile needs.

4.2 Proprietary Data Rights Periods

The SIMSWG endorses the concept of a limited but finite period of proprietary data rights beyond release of mission data to Key Projects or PI's for the purpose of optimizing the scientific return from the mission. A nominal proprietary period of a year seems reasonable and defensible in most cases and we believe that the peer review process is the appropriate mechanism for exceptions, which can be requested and defended in each specific case.

Critical to this is the definition of the word "released". Released data are those that reach some level of maturity, stability and quality assurance. This is sufficiently complicated and project dependent that the SIMSWG feels it appropriate to defer the exact definition of "released" data to the Science Team in consultation with the ISC.

One class of data is viewed as exceptional and not subject to any proprietary period: those involving the astrometric grid. The SIMSWG recognizes that substantial science involving fundamental questions may be investigated using grid star data and that investigators pursuing those questions may possibly be placed at some disadvantage. Nevertheless, it is felt that the grid is being constructed for the benefit of the entire mission and is so fundamental to the success of the mission, that the data on it's detailed properties should not be delayed for any reason - that those data should be made public as soon as they meet the criteria for release as described above.

4.3 Intermediate Reductions

The SIMSWG, in conjunction with the Project, strongly supports a full-up intermediate data reduction, nominally at the 2.5 year point in the mission. This is critical to provide sufficient time to fully shake down the data reductions procedures, calibration procedures, and algorithms that will be required at the end of the 5 year mission. Further, some considerable science should be essentially *mature at the end of this shorter interval. A decision whether to consider an extension to the mission will surely depend heavily on the success and quality of these shorter time-base results.*

4.4 Redundancy in the Data Reduction Model

Following the experience with Hipparcos, there is a significant question whether the mission should adopt a fully redundant, ie., parallel, data reduction model. Arguments against are primarily the high cost, but these are not easily dismissed. It is the sense of the SIMSWG that the final recommendation on this issue be made by the Science Team in consultation with the ISC. However, the SIMSWG did feel that at this point, some sort of partial redundancy or "shadowing" model of data reduction, accompanied by significant membership on the Science Team of specialists in these data reduction areas, could well be sufficient and cost effective.

5 The Science Requirements Document

5.1 Purpose of the Science Requirements Document

The Science Requirements Document serves several purposes.

- The SRD is intended to represent the clear statement of the advances in science which can be expected to result from the Space Interferometry Mission. The science program is a consensus of research topics put forward by the science community to be addressed by SIM. As representatives of the astronomical community interested in the capabilities of SIM, the Space Interferometry Mission Science Working Group have continued the work of other groups in the past few years, including the NRC Astronomy and Astrophysics Survey (Bahcall 1991) Committee and the Space Interferometry Science Working Group.
- The SRD states, as specifically as possible, usually with numerical estimates of performance, the measurements which must be made by SIM to achieve the science objectives. There are two levels of performance: Goals and Recommendations; these terms are defined below.
- The SRD also states the performance required to achieve a Science Floor. The Science Floor represents the minimal science capability, below which the mission's scientific productivity comes into question.
- The SRD necessarily represents a synthesis of science objectives on one hand, and technical feasibility on the other. If the balance between technical feasibility and scientific objectives has to be changed (e.g. an instrument requirement cannot be met), this document is the first point of reference for determining the impact on science objectives.

5.2 Scope of the Science Objectives

SIM is an optical interferometer operating in Earth-trailing orbit. Science programs have been developed which impose requirements on the design of the spacecraft, and its operation as a flight instrument. This mission offers the ability to make measurements with an accuracy far in excess of ground-based observations, or any other space mission in the near term. SIM therefore has tremendous potential for unexpected results.

It is anticipated that a substantial part of the mission can be devoted to observational programs which are proposed by the science community. In addition, programs may be developed during the mission operations phase, as scientific results are obtained from early mission operations. These new programs will necessarily be constrained by the capabilities of the instrument in orbit. This document provides a reference for evaluating the feasibility of new science topics relative to those contained herein.

5.3 Terminology

There are three levels of science performance considered in this document. These terms were discussed in some detail, and agreed to by the SIM Project, at the Second SIMSWG Meeting. Although Headquarters and the Project have since decided to view these only as recommendations, the distinction between these terms is important, so care was taken to use them consistently:

- Science Goal: The Project should make a "best effort" to design SIM in order to accomplish the Science Goals.
- Science Recommendations: The Project should perform the initial design of SIM to accomplish the science listed in the Science Recommendations.
- Science Floor: If some items in the Science Floor list cannot be accomplished, the viability of the Mission will have to be re-evaluated.

5.4 Prioritization of Science Objectives

There is no explicit prioritization of SIM science objectives in the SRD. The major science topics in this SRD are anticipated to require less (elapsed) time than the anticipated SIM lifetime. Detailed estimates of the total observing time required for each topic are not included in this version of the SRD. Some topics (imaging of extended fields; astrometry of very faint targets) involve long observations, and it is very likely that not all such topics will be possible within a reasonable mission lifetime.

If the Project is unable to deliver the performance required to meet the Science Recommendations, this document provides a means of selecting a reduced set - namely those which meet the Science Floor. Further, in a separate communication, the SIMSWG has suggested the order in which capabilities should descope, everything being equal.

5.5 Specification of Science Requirements

Requirements in this SRD are specified at project Level 1. That is, to the extent possible, the stated requirements are not intended to imply a particular architecture of mission design at all, and are simply a specification of the physical quantities to be measured, etc. For most of the science topics described below, the following set of specifications are provided.

1. Summary statement of the scientific objective.
2. Specify the minimum science which may be achieved if the main objectives cannot be met.
3. A brief statement of the observational technique to be used, and the data which must be collected (with errors if appropriate).
4. Translate the science observation requirement into goals on the instrument performance (to meet science objective), and requirements on the instrument (to meet the minimum useful science).

5. Specify operations requirements which are necessary to achieve the science objective.

In the following Sections, science topics are divided according to the anticipated major instrumental requirement, of which four are identified:

- Global (wide-angle) precision astrometry
- Local (narrow-angle) precision astrometry
- Rotational synthesis imaging
- Interferometric nulling-imaging

6 SRD: Astrometric Science Requirements

6.1 Instrument and Mission Requirements for All Astrometry Programs

The following two tables summarize the Goals, Recommendations and Floor specifications for the wide-angle and narrow-angle astrometric programs discussed in the remainder of this section, i.e. each listed requirement is stringent enough to satisfy the corresponding individual requirement of all of the astrometric programs. In this section and the rest of the science sections, required precisions are to be understood as one standard deviation uncertainty for the quantity being discussed.

Wide-Angle Astrometry Science Requirements

`Parameter`	`Goal`	`Recommend`	`Floor`	`Comment`
Field of regard	$\geq 15°$	$\geq 15°$	$\geq 15°$	
Single observation astrometric accuracy	$\leq 4\ \mu$as	8 μas	20 μas	derived
Overall mission astrometric and parallax accuracy	$\leq 2\ \mu$as	4 μas	10 μas	6.7, 6.8, 6.9, 6.12
Minimum star brightness	V=20	V=20	V=16	6.8, 6.9, 6.10
Observation time interval	10 yr	5 yr	5 yr	
Proper motion accuracy	≤ 1 μas yr^{-1}	2 μas yr^{-1}	10 μas yr^{-1}	6.5, 6.6, 6.10, 6.11

Narrow-Angle Astrometry Science Requirements

`Parameter`	`Goal`	`Recommend`	`Floor`	`Comment`
Field of regard	3°	1°	1°	6.10
Single measurement astrometric accuracy	0.15 μas	0.5 μas	3 μas	6.2, 6.3, 6.4
Minimum star brightness	V=13	V=13	V=13	
Proper motion accuracy	0.5 μas yr^{-1}	0.5 μas yr^{-1}	5 μas yr^{-1}	6.10
Observation time interval	10 yr	5 yr	5 yr	

Astrometric Use of Spectral Data

SIM will make use of the entire optical band in determining star positions, subject to the limitations of CCD detector sensitivities and accumulated reflection losses. This provides improved sensitivity, star positions are not a function of wavelength. Further, indications of a dependence of position on wavelength may suggest that the object is a double.

Sky Coverage

SIM must be able to perform astrometric observations of any star in the sky at any time during a period of no less than 6 months, with the period defined relative to the ecliptic longitude of the star. This allows the maximum sensitivity of annual parallax measurements which requires observations be performed at close to opposite ends of an Earth orbit diameter.

In addition, SIM is required to be able to observe 4π steradian coverage of the celestial sphere over the course of 5 months to account for closure of the grid. Permanent "gaps" in observability are not allowed.

Mission Lifetime

The Science Goals for the detection and study of Nearby Terrestrial Planets and Substellar Companions to Solar-Type Stars (§§ 6.2 – 6.4) imply a mission lifetime of at least 10 years, because giant planets with formation and evolutionary histories similar to Jupiter and Saturn are expected to have orbital periods on the order of a decade or more. The accuracy of the proper motions needed to accomplish many of the astrometric Science Requirements imply a mission lifetime of at least 5 years. A mission lifetime significantly less than 5 years would have a detrimental impact on nearly all the astrometric projects, and those which have stellar proper motions as the primary observable would be severely affected.

Orthogonal Astrometric Errors

Almost all of the science programs require the measurement errors in orthogonal coordinates on the sky (RA, Dec; ecliptic coordinates β, λ; etc.) on positions and proper motions to be approximately equal. Parallaxes are based on fitting to an ellipse on the sky whose orientation and axial ratio are known a-priori to sufficient precision, and are not subject to this requirement.

Stated formally, the error ratio (using *mission* data) for parallaxes and proper motions of a science target must be $0.9 < |E_{\alpha,\delta}| < 1.1$. The same requirement must be met by the parallaxes and proper motions of stars in the global astrometric grid. Reason: Minimizes constraints on operational scenarios and maximizes observing efficiency.

Continuous viewing period

The maximum time period (scan length) for which science data on a given target can be obtained continuously must be no shorter than 10 minutes. This requirement need not be satisfied at all times, but must be satisfied at some time of year and over a sufficient range of ecliptic longitudes as to allow mission specifications for parallaxes to be met.

This specification is for faint targets requiring on-target times longer than the maximum scan length which must be observed in multiple scans, scheduled almost consecutively if required. Since a significant mission fraction may be devoted to faint targets, these observations must maintain a reasonable efficiency.

Throughput

The requirements listed in this document do not pretend to be comprehensive and yet indicate the need to measure several thousand objects, many at the faint limit. Anticipating that there will be many worthy projects with many additional objects over the whole range of brightness, we specify that the nominal 5 year mission be able to observe with sufficient efficiency that the equivalent of 3×10^4 objects of V= 16 could have 4 μasparallaxes determined.

Response to Targets of Opportunity

The instrument is capable of responding to changing observing programs, allowing a program for *Targets of Opportunity.* Many events, ie. gravitational lensing events, supernovae in distant galaxies, etc, can be accommodated in a four day data up link cycle and this should suffice as a design parameter.

Extended Spectral Coverage

Although not called out in the requirements, there continues the concern that problems of major scientific importance will be excluded by the lack of a near IR detector in one of the interferometers. We expect the imminent release of the initial 2-MASS observations to put this into sharp focus. Adding this capability should remain among the highest priorities should mission funds allow the instrument to be expanded beyond meeting the basic requirements listed here.

Observing efficiency

Detailed estimates of the required observing efficiency are not given in this version of the SRD. They are a complicated function of many instrument and mission parameters, as well as target brightness, and angular distribution of science targets on the sky, and hence require extensive simulation.

Subsequent versions of the SRD will contain information on the amount of time required to observe objects of various magnitude classes and science goals/recommendations/floor for the total amount of mission time allocated for science.

6.2 Earth-Sized Planets

Summary of Science Objectives

The Science Objective is to detect or rule out the presence of earth-sized planets orbiting nearby solar-type stars and study their characteristics in order to learn about the formation and evolution of planetary systems that might include habitable planets. In addition we need to identify good targets for the Terrestrial Planet Finder mission.

Science Goal

Science Goals are to search for evidence of earth-sized planets orbiting in or near the habitable zones of 50 of the most suitable solar-type stars, derive orbital solutions and planet masses where feasible and search for evidence of additional planets in those systems yielding orbital solutions. These terms translate as follows:

- earth sized: 0.5 to 2.0 earth masses
- solar-type: F, G, K, early M dwarfs (roughly 0.5 to 2.0 solar masses)
- habitable zone: periods 0.2 to 5 years (depends strongly on the spectral type of the star)
- most-suitable: nearest candidates without any evidence (despite close scrutiny) for companions which would interfere with the formation or survival of earth-sized planets in the habitable zone. A high-priority task for the near future would be to select candidates for the best targets, and to carry out any preliminary observations or analysis which are needed to pick the final list of targets.

Science Recommendation

The Recommendations are to search for evidence of earth-sized planets orbiting in or near the habitable zones of the 5 most suitable solar-type stars, derive orbital solutions and planet masses where feasible and search for evidence of additional planets in those systems where earth-sized planets are detected.

The instrumental requirements are easier for the Recommendation than for the Goal because the target list is smaller and therefore the targets can be closer.

Science Floor

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.

Instrument and Operations Requirements

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Astrometric signature	0.3 μas	1 μas	N/A	Note 1
Astrometry type	Narrow-Angle	Narrow-Angle	N/A	
Star brightness	$V < 9$	$V < 7$	N/A	Note 2
Schedule	Every $\sim$ 3 months for 5-10 years	Every $\sim$ 3 months for 5-10 years	N/A	
Number of visits:				
- to detect	80 in 5 years	80 in 5 years	N/A	
- to derive orbits	160 in 5 years	80 in 5 years	N/A	
- to search for additional planets	240 in 5-10 years	80 in 5 years	N/A	
Number of targets:	50	5	N/A	

Note 1: The astrometric signature is stated as the orbital semi-major axis for a system with typical parameters: a planet of 1 earth mass in a 1 AU orbit around a 1 solar-mass star 10 pc from earth for the Goal, and 3 pc for the Recommendation. Individual positional measurements would have to be somewhat more accurate to allow such orbits to be detected with modest data sets.

Note 2: Based on a preliminary selection of target lists with the faint cutoff set at absolute V magnitude 9, corresponding to early M dwarfs.

6.3 Large Terrestrial Planets

Summary of Science Objectives

The objectives are to detect or rule out the existence of large terrestrial planets orbiting nearby main-sequence stars and study their characteristics in order to learn about the role of rocky cores in the formation and evolution of planetary systems.

Science Goal

The Goal is to search 200 main-sequence stars for evidence of large terrestrial planets which formed as rocky cores in the region closer to their parent stars than the inner boundary of the ice condensation zones in their proto-planetary disks, to derive orbital solutions and planet masses where feasible and to search for evidence of additional planets in those systems where planets are detected. These terms translate as follows:

- terrestrial: 2 to 20 earth masses
- main-sequence stars: A through M dwarfs (O and B are too rare and therefore too distant). The targets should be known not to have companions which would interfere with the formation or survival of large terrestrial planets in the search zone. A high-priority task for the near future would be to select candidates for the best targets, and to carry out any preliminary observations or analysis which are needed to pick the final list of targets.
- inside inner boundary of the ice condensation zones: periods 1 to 10 years (depends on the spectral type of the star)

Science Recommendation

As a Recommendation we need to search 50 main-sequence stars for evidence of large terrestrial planets. The only difference between the Goal and the Recommendation is the number of targets to be searched. The instrumental requirements are easier for the Recommendation than for the Goal because the target list is smaller and therefore the targets can be closer.

Science Floor

The Floor is to search 20 main-sequence stars for evidence of large terrestrial planets. The frequency of large terrestrial planets is unknown, but may be as low as a few percent. A target list of 20 stars is about the minimum to allow a meaningful limit in the case that large terrestrial planets occur infrequently.

Instrument and Operations Requirements

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Astrometric signature	2 μas	4 μas	6 μas	Note 1
Astrometry type	Narrow-Angle	Narrow-Angle	Narrow-Angle	
Star brightness	$V < 14$	$V < 13$	$V < 12$	Note 2
Schedule	Every $\sim$ 3 months for 5-10 years	Every $\sim$ 3 months for 5-10 years		
Number of visits:				
- to detect	60 in 5 years	20 in 5 years	20 in 5 years	
- to derive orbits	60 in 5 years	40 in 5 years	40 in 5 years	
- to search for additional planets	60 in 5-10 years			
Number of targets:	200	50	20	

Note 1: The astrometric signature is stated as the orbital semi-major axis for a system with typical parameters: a planet of 5 earth masses in a 2 AU orbit around a 1 solar-mass star 16 pc from earth for the Goal, and 13 pc for the Recommendation, and 10 pc for the Floor. Individual positional measurements would have to be somewhat more accurate to allow such orbits to be detected with modest data sets.

Note 2: The early-type stars will mostly be naked-eye objects; the faint limit of the sample to be observed is not well established because it depends on which M stars are included as targets.

6.4 Substellar Companions to Main-Sequence Stars

Summary of Science Objectives

The objective here is to detect or rule out the presence of giant planets and brown dwarfs orbiting nearby main-sequence stars and study their frequency and characteristics in order to learn about the formation and evolution of planetary systems and the transition region between giant planets and brown dwarfs.

Science Goal

For a Goal we need to search for evidence of giant planets and brown dwarfs orbiting 1000 of the most suitable main-sequence stars, derive orbital solutions and companion masses where feasible and search for additional planets in systems where giant planets are detected. These terms translate as follows:

- giant planets: 20 earth masses to 30 Jupiter masses
- brown dwarfs: 2 to 80 Jupiter masses
- orbiting: periods 0.5 to 50 years (there is a strong relationship between the mass detection threshold and the period)
- most-suitable: nearest candidates without any evidence (despite close scrutiny) for stellar companions which would interfere with the formation or survival of detectable giant planets and brown dwarfs. There needs to be some discussion of the optimum mix of the number of targets as a function of spectral type. A high-priority task for the near future would be to select candidates for the best targets, and to carry out any preliminary observations or analysis which are needed to pick the final list of targets.

Science Recommendation

The Recommendations include searching for evidence of giant planets and brown dwarfs orbiting 500 of the most suitable solar-type stars and deriving orbital solutions and companion masses where feasible.

Science Floor

As a minimum we need to search for evidence of giant planets and brown dwarfs orbiting 200 of the most suitable solar-type stars, to derive orbital solutions and companion masses where feasible and, in addition, to derive astrometric orbits where feasible for those stars where precise radial-velocity observations have provided orbits suggesting substellar minimum masses.

Comments The main difference between the Science Goal and the Recommendation and Floor is the number of systems searched. The numbers of targets are based on the present best guess that about 1-2% of solar-type stars have brown dwarf companions, while the frequency of giant planets may not be much larger. The instrumental requirements are easier for the smaller samples, because you don't have to reach out to as large distances in order to get enough targets. The operational requirements scale roughly by the number of targets.

The study of substellar companions found by precise radial velocities has been included in the Science Floor. SIM should be able to provide astrometric orbits for essentially all of these systems, thus providing the orbital inclination and removing the ambiguity inherent in $m \sin(i)$ from spectroscopic orbits. By the time that SIM flies we should expect that the number of spectroscopic substellar companions will have grown significantly, hopefully to include companions with longer periods reminiscent of the giant planets in our own solar system. Nevertheless, it would be useful to prepare a list of all the radial-velocity candidates known now, with projections of what could be learned with the help of SIM, and an evaluation of the instrumental and operational performance needed.

Instrument and Operations Requirements

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Astrometric signature	6 μas	6 μas	6 μas	Note 1
Astrometry type	Wide-Angle	Wide-Angle	Wide-Angle	
Star brightness	$V < 13$	$V < 13$	$V < 13$	Note 2
Schedule	Every $\sim$ 3 months for 5-10 years	Every $\sim$ 3 months for 5-10 years	Every $\sim$ 3 months for 5-10 years	
Number of visits: - to detect - to derive orbits - to search for additional planets	 20 in 5 years 40 in 5 years 60 in 5-10 years	 20 in 5 years 40 in 5 years 60 in 5-10 years	 20 in 5 years 40 in 5 years 60 in 5-10 years	
Number of targets:	1000	500	200	

Note 1: The astrometric signature is stated as the orbital semi-major axis for a system with typical parameters: a planet of 0.1 Jupiter masses in a 2 AU orbit around a 1 solar-mass star 30 pc from earth for the Goal. Individual positional measurements would have to be somewhat more accurate to allow such orbits to be detected with modest data sets.

Note 2: The faint limit of the sample to be observed is not well established because it depends on which M stars are included as targets.

6.5 Dynamics and Evolution of Binary Stars

Summary of Science Objectives

Binary stars and stellar masses:

The objective is to obtain precise masses for stellar constituents in spectroscopic binaries in order to refine the mass-luminosity relation for sub-solar mass stars in the Galactic disk and, for the first time, to determine directly the mass-luminosity relation for metal-poor stars in the Galactic halo.

The mass-luminosity relation is fundamental to our understanding of both the mass distribution in the Galaxy and of stellar structure, particularly in determining the exact location of the hydrogen-burning limit. Fine structure in the M/L relation corresponds to changes in the physics of stellar interiors. At present, the relation for solar-metallicity stars less massive than $0.5\,M_\odot$ is defined by only 20 stars. All are astrometric binaries, and the masses are determined to a typical precision of 20 to 40 percent. Mass determinations for metal-poor stars are effectively non-existent. Relative orbits for both types of systems should be determined with comparable precision using the forthcoming Keck interferometer, but such observations require absolute astrometric calibration before masses can be determined. SIM can determine high-accuracy parallaxes and photocentric orbits for known, nearby, late-type spectroscopic binaries in both the general field and in clusters, achieving mass estimates with a precision of better than 2 percent.

Brief Statement of Technique

SIM can contribute to this fundamental issue through determining accurate distances for binary systems with accurate relative astrometric or spectroscopic orbits; through absolute astrometry of resolved systems; and through absolute astrometric determinations of photocentric orbits of unresolved spectroscopic systems. Even considering proposed astrometric instruments and mission, SIM appears to be unique in its ability to make this last measurement.

The combination of measuring both the parallax and the photocentric orbit of a double lined spectroscopic binary provides a complete description of the system. The parallax provides the absolute magnitude of the combined light. The shape of the photocentric orbit gives the inclination which, combined with $a_1 sin(i)$ and $a_2 sin(i)$ from the spectroscopic measurements, allows direct determination of the individual masses. The flux ratio of the two components can be derived in several ways: directly, if the system is resolved (>10 mas, SIM; >5 mas, Keck IR interferometer); from the relative line-strengths in the spectra; and from the wavelength dependence of the absolute dimension of the photocentric orbit derived by SIM.

Science Goal

Since $L \propto M^3$, the scatter in the mass-luminosity relation is dominated by uncertainties in mass, rather than luminosity. Our goal is to determine masses accurate to better than 1% for stars with $1.0 \geq M/M_\odot > 0.08$, corresponding to $20 > M_V > 4$ or $11 > M_K > 3$. This demands uncertainties of no more than 0.3% in sin(i), since the derived mass varies with the cube of the de-projected semi-major axis. In order to sample the full mass-range of field stars, and to characterize metallicity dependences, we require a sample of at least 180 spectroscopic binaries, distributed among the following categories:

-100 Disk dwarfs drawn from the general field

-30 binaries from the Hyades, Pleiades, Praesepe and other open clusters

-30 Halo F, G, K field subdwarfs

Note that even for the nearby Hyades cluster the individual parallaxes from the HIPPARCOS mission are good to only slightly better than 5%.

Science Recommendation

As the basic recommendation toward the stellar mass-luminosity relation we specify parallax determinations to better than 0.25 percent for all of the stars currently contributing to the M/L relation. To this we add parallax measurements to better than 0.25 percent and $\sin i$

determinations to better than 0.5 percent for 100 spectroscopic binaries drawn from the lower main-sequence (masses below $0.8\,M_\odot$). This requires:

-70 Disk dwarfs drawn from the general field
-30 Halo F, G, K field subdwarfs

Science Floor

General comment: the main difference between Goal/Recommendation/Floor rests in both the number of targets and the apparent magnitude distribution.

Binary stars and stellar masses As a bare minimum we require parallax determinations to better than 0.25 percent for all of the systems currently contributing to the M/L relation and the addition of parallax measurements to better than 0.25 percent and $\sin i$ determinations to better than 0.5 percent for 75 spectroscopic binaries, drawn as follows:

-50 Disk K and M dwarfs drawn from the general field
-25 Halo G, K field subdwarfs

Instrument and Operations Requirements

Mass-Luminosity Relation	`Goal`	`Recommendation`	`Floor`	`Comment`
Astrometric accuracy	$5\,\mu$as	$10\,\mu$as	$50\,\mu$as	Note 1
Star brightness	$V < 18$	$V < 15$	$V < 15$	
Proper motion	$2\,\mu\text{as}\,\text{yr}^{-1}$	$5\,\mu\text{as}\,\text{yr}^{-1}$	$10\,\mu\text{as}\,\text{yr}^{-1}$	
Measurement baseline	5 yr	5 yr	5 yr	Note 2
Number of visits	20	10	10	

Note 1: Wide-Angle Mode: The astrometric accuracy for Goal and Recommendation are the required precision of a single observation while for the floor it is that of the mission.

Note 2: The aim is for at least 10 observations covering > 50 percent of an orbit.

Comment: All of the targets chosen will be spectroscopic binaries with periods < 10 yr. High-precision, ground-based observations will be used to determine all orbital parameters save the orbital inclination. The latter parameter, and the parallax, will be determined using SIM. Some systems can be expected to be resolved; in others, the photocentric orbit will be determined. In either case, at least 10 well-distributed observations will provide accurate measurement of both the parallax and the orbital inclination.

6.6 Stellar Death and Standard Candles - Luminous Stars in the HR Diagram

Summary of Science Objectives

Luminous stars in the HR diagram:

The HR diagram remains the fundamental tool for investigating stellar evolution. OB main-sequence stars, planetary nebulae and AGB stars are all short-lived objects which are, as a result, rare within the immediate Solar Neighborhood. Parallaxes, and therefore luminosities, are therefore constrained with very low precision. Accurate distances will permit precise positioning of these objects on the HR diagram, testing theoretical predictions for high-mass star and post giant-branch evolution, particularly the effects of stellar winds and dust-driven mass loss.

Standard candles:

Cepheid variable represent the first step in the extragalactic distance scale. HIPPARCOS observed over 200 variables, but was able to determine a parallax of modest accuracy for only one - Polaris, which proves to be a non-standard overtone pulsator. With typical distances of 1 to 4 kpc, SIM can determine trigonometric parallaxes to a precision of better than 1 percent for all of these stars, permitting not only a firm calibration of the period-luminosity relation for Galactic Cepheids, but also an accurate measurement of the intrinsic dispersion about that relation. Since these stars are drawn from Galactic radii of from 7 to 12 kpc, these data will test whether a single relation can describe adequately all Galactic stars, or whether systematic (metallicity-dependent?) trends need to be taken into account.

RR Lyrae stars provide an independent check on the distance scale within the Local Group. Although of higher space density than Cepheids, HIPPARCOS again provides reliable parallaxes for a handful of stars, and there continue to be discrepancies at the 10-15% level between the metal-poor field-RR Lyrae (but not cluster RR Lyrae) scale and the Cepheid scale. SIM can provide high-precision parallax data for RR Lyraes within 2 kpc, and a direct comparison with both Cepheids and the globular cluster distances.

Brief Statement of Technique

SIM observations will be used to determine the parallaxes of these sources using standard techniques. Since the majority of the Cepheids lie at distance of 2 kpc or more, interstellar reddening is clearly a potential problem. In the particular case of the Cepheids, the uncertainties in the derived period-luminosity relation can be minimized by limiting the sample to stars with foreground reddening of $\mathrm{E}_{B-V} < 0.3$ mag. Since the absorption at $2\mu m$, A_K, is $\sim 0.3E_{B-V}$ or $\sim 0.1\mathrm{A}_V$, ground-based infrared observations of those stars can provide the necessary bridge to the LMC, and hence a direct calibration of the overall extragalactic distance scale. A low-reddening RR Lyrae sample can be defined.

Science Goal

Parallax determinations to better than 5 percent for 50 RR Lyraes with [Fe/H]< -1.5 and the $\sim$ 100 Cepheids with foreground reddening of $\mathrm{E}_{B-V} < 0.25$ mag. (distances up to 5 kpc) should be obtained as should parallaxes to a similar precision for 100 OB stars, 50 planetary nebulae and 50 AGB stars, delineating their distribution across the upper regions of the HR diagram. In choosing the targets, preference would be given to stars identified as members of stellar associations thought to include Cepheids.

Science Recommendation

Parallax determinations to better than 5 percent for 30 metal-poor RR Lyraes and 50 Cepheids with foreground reddening of $E_{B-V} < 0.25$ mag. (distances up to 3 kpc) and parallaxes to a similar precision for 50 stars, 25 planetary nebulae and 20 AGB stars are required.

Science Floor

At a minimum we need to obtain trigonometric parallax estimates accurate to better than 10% for the 29 Galactic Cepheids which are identified as members of nearby stellar associations. In addition, parallax measurements should be made of between 3 and 4 upper main-sequence stars within each association (120 stars); of 20 field asymptotic giant-branch stars; and of 10 central stars in planetary nebulae.

Instrument and Operations Requirements

Luminous stars	Goal	Recommendation	Floor	Comment
Astrometric accuracy	10 μas	20 μas	30 μas	Note 1
Star brightness	V < 13	V < 13		
Proper motion	3 μas yr^{-1}	10 μas yr^{-1}	10 μas yr^{-1}	
Measurement baseline	5 yr	5 yr	5 yr	
Number of visits	20	10	10	

Note 1: Wide-Angle Mode: standard parallax observations.

6.7 The Ages of Globular Clusters

Summary of Science Objectives

We propose to determine the age and the evolutionary state of twelve representative globular clusters (GC) in the Milky Way plus two GCs that appear to have undergone a complex chemical evolution/enrichment.

Brief Statement of Technique

The primary uncertainty in determining the ages of GCs using the "ΔV" technique involves determining the absolute magnitude of the Horizontal Branch (HB, Sarajedini et al. 1997). This is usually accomplished by substituting the absolute magnitude of the RR Lyrae stars, a quantity with a very controversial dependence on metallicity. Additionally, reddening must be estimated from integrated color, again depending on the adopted metallicity. Correction for interstellar absorption assumes standard ratios.

A direct measurement of distance to a representative set of GCs would eliminate most of the errors in this process, reducing the uncertainties in the age determination by at least a factor of two. The exact numbers involved depend on the investigator, but current uncertainties are put at around 1 Gyr and they should be reduced to 0.5 Gyr.

Globular Clusters for Age and Chemical Evolution Determination

NGC	Name	[Fe/H]	KT	HBR*	$d_\odot$	R_{GC}	V(HB)	Comments
4590	M68	-1.80	YH	0.44	9.9	9.6	15.6	$-2.5 \leq$[Fe/H]< -1.7
7078	M15	-2.15	OH	0.72	10.2	9.9	15.8	
6397		-1.91	OH	0.93	2.2	6.1	12.9	
	Arp 2	-1.70	OH	0.86	27.6	21.5	18.2	Sag dSph
288		-1.40	OH	0.95	8.1	11.2	15.3	$-1.7 \leq$[Fe/H]< -1.0
5272	M3	-1.66	YH	0.08	9.7	11.7	15.6	
5904	M5	-1.40	OH	0.37	7.3	6.0	15.0	
362		-1.27	YH	-0.87	8.0	8.8	15.3	
104	47 Tuc	-0.71	D	-1.00	4.1	7.3	14.1	$-1.0 \leq$[Fe/H]
6171	M107	-0.99	OH	-0.76	6.3	3.6	15.6	
6652		-0.89	OH	-1.00	9.4	1.9	15.9	
	Ter 7	-0.36	YH	-1.00	23.0	14.3	17.8	
5139	ω Cen	-1.62			5.1	6.3	14.5	Peculiar Chemistry
6656	M22	-1.64		0.91	3.2	5.0	14.2	

* HBR=(#Blue–#Red)/(#Blue+#Variable+#Red)

GCs in the Milky Way exhibit a range of HR diagram morphologies. It has been proposed that some of this is due to a "second parameter", variously identified as a spread in age or in Helium abundance. Determining the distances of a selected group of GCs covering the range of this variation would improve our understanding of its source and our confidence in the reliability of the deduced ages.

The kinematics of the GC system evoke another whole series of important science issues, which will be covered in § 6.9.

A representative set of GCs which cover the range of kinematic types, metallicities and HB morphologies are given below. The columns give: the NGC (1) and common (2) names, metallicity (3), Kinematic Type (OH = Old Halo, YH = Younger Halo, D = Disk) (4), Horizontal Branch Ratio (HBR=1.00 for a completely blue HB, -1.00 for red) (5), distance from the Sun (6), distance from the Galactic Center (7) and apparent magnitude of the Horizontal Branch (8). Generally, the apparent magnitude of the tip of the Giant Branch is about 2 magnitudes (V) brighter than the HB. All but the solar distances and the data for the last two objects are taken from Chaboyer et al (1996), the remainder are from Harris (1996).

Mission statements are derived from this list.

Science Goal

The Goal is to measure the distances for all the listed systems to an accuracy of 5%. This requires 2 μas parallaxes down to V=16. Each system should have the the distances determined to ten member stars. This will suffice to identify non-members and eliminate or minimize the effects of long period binaries. Note that objects well out from the cluster centers may be targeted, which will eliminate the need for observing in a crowded field mode.

Science Recommendations

Compared to the Goals, above, distances accurate to 5% or better are required to these systems except the two most distant. The remainder are closer than 11 kpc and require parallaxes good to 4 μas. The two exceptions represent special cases and will contribute scientifically even with 10% distances.

Science Floor

We require distances accurate to 6% to the five systems within ~ 6 kpc of the Sun. There are 11 other systems listed in Harris (1996) inside this distance limit and one or two of those may be added.

Instrument and Operations Requirements

Summary for Globular Clusters

Globular Clusters	Goal	Recommendation	Floor	Comments
Astrometric accuracy	2 μas	4 μas	10 μas	Wide-Angle
Star Brightness (V)	13.5	13.5	13.0	
Number of Objects	120	120	80	
Star Brightness (V)	16.0			Distant Clusters
Number of Objects	20			

6.8 Stellar Dynamics of the Galaxy

Summary of Science Objectives

The fundamental questions here are to understand the mass distribution and the dynamics of our Galaxy. In particular, we ask (1) What is the size of the Galaxy? (2) What is the distribution of mass in our Galaxy? and (3) What are the kinematics of stars in the outer halo as well as in and near the plane? By answering these questions, we were learn about the nature of the dark matter and the formation history of the Galaxy.

Brief Statement of Technique

These are classical problems, measuring the size, characterizing the rotation of the Galaxy and determining its mass distribution. They are complicated by the need to determine the deviations from pure circular rotation associated with the recently discovered central bar, and the amount and distribution of dark, as well as visible, matter.

By measuring the distances to stars in Baade's window, we can determine R_0 with an uncertainty of 1 kpc/$\sqrt{N}$, where 1 kpc is the width of the bar at Baade's window. If we determine astrometric distances to Bulge red clump stars, then these stars can be used as calibrators to trace the size and shape of the Galactic bar. Alternatively, we can determine astrometric distances directly and determine the bar width and angle.

In the outer Galaxy, we use tidal streamer stars to trace the potential (Johnston et al. 1999). By exploiting the fact that these stars lie along a single orbit, we can measure the galactic potential in the outer Galaxy to an accuracy of a few percent. This technique requires proper motions and radial velocities (to be obtained separately), but does not require parallaxes.

We complement the measurements of the potential with observations of correlations between metallicity and kinematics. We would want to explore stellar orbits as a function of position in the Galaxy and metallicities to infer the galaxy formation history (e.g., Eggen, Lynden-Bell & Sandage 1962; Searle & Zinn 1978).

Within 10 kpc from the Galaxy, we use a sample of bright late type stars to trace the galactic potential. Here, we use the classic Jeans equations analysis to determine the potential.

Science Goals

In the inner Galaxy, we would like to determine the width and orientation of the bar by determining the median distance to stars along three lines of sight. With 50 stars along each line of sight, we should be able to determine R_0 with an accuracy of 2%.

In the outer Galaxy, we would like to trace the tidal tails of the Magellanic Clouds, Sagittarius, Fornax, Leo I and Leo II. Recent work has traced tidal tails in the first two systems. It is likely that tidal tail stars will be found for the other two systems over the next few years. With five systems, we will be able to measure the galactic mass profile as a function of radius with an accuracy of better than 5%. These observations will also measure the shape of the galactic potential. We would want to obtain five dimensional phase space information for 100 stars in each tidal tail. Totten & Irwin (1998) have identified tens of Carbon stars ($M_V = -2.5$) in the Sagittarius tidal tail. This project will require pre-launch surveys to identify candidate objects. The proper motion accuracies should exceed the velocity width of the tails.

We would like to determine the relationship between metallicity and galactic orbit for a large population of halo stars. Here, we will be limited by our ability to measure parallax so that we will want to focus on stars within 10 kpc of the Sun.

A definitive determination of the Galaxy rotation law requires careful sampling of the kinematics throughout the plane of the Galaxy. It is important to follow the stellar kinematics well above the plane if the full vertical distribution of gravitating matter is to be sampled. The recent determination of the density of matter at the Sun's location using HIPPARCOS data strongly constrains any dark matter component to be spherical. If it is required to explain a constant rotation curve at $2\,R_0$ it is necessary to probe the potential up to 20 kpc out of the plane.

The biggest difficulty with the latter project will be the small number of probable targets at those heights. With little reddening and $M_V = 0.0$ for the typical K giant, the likely target, the objects are $V = 16.5$ and brighter. The velocities will again be limited in accuracy by the parallaxes. A goal of $2\,\mu$as accuracy for the parallaxes will limit uncertainties in the parallaxes and velocities to 4%. A guess is that 100 objects will be necessary to define the basic outlines of the velocity distribution at each level, and that this should be done for every 5 kpc above the plane, out to 20 kpc These numbers are very uncertain and in need of detailed study. An infrared capability would enable us to probe the potential closer to the plane and in the inner Galaxy.

Science Recommendations

In the inner Galaxy, we would like to determine the distances to 50 red clump stars in Baade's window. These can then be used as calibrators through out the bar.

The recommendations involve the same questions and the same limitations due to errors as described above. Here, we want to trace the Magellanic Stream tidal tail and the Sagittarius dwarf tidal tail. With 100 stars in the Sagittarius tidal tail, we should be able to measure the mass of the Galaxy to an accuracy of 4% and the flattening of the potential to an accuracy of 3% (Johnston et al. 1998).

We would like to obtain accurate orbits for at least 400 halo stars so that we can explore correlations between metallicity and kinematics. This large a sample is required to detect 10% variation in velocity dispersion with metallicity.

The determination of dependence of the Galactic potential with distance above the plane is likewise limited by parallax accuracy. A parallax error of 4 μas permits the measurement of the vertical density and potential to about 5 kpc, and less accurately to 10 kpc. The kinematics of the outer halo can still be addressed properly at this lower accuracy level. A total of about 400 stars would be required for this part of the project.

Science Floor

A substantial amount of the science described above can be retained with reduced mission accuracies and throughput. Parallaxes accurate to $10\,\mu$as could flesh out the basic size and orientation of the bar and yield a value for R_0 good to 5–6%. The velocity curve out to $2R_0$ could be determined to 10% with such parallaxes and proper motions no more accurate than $100\,\mu\mathrm{as\,yr}^{-1}$. The same is true for the kinematics of the halo, again limited almost entirely by parallax errors. In each of these cases we would reduce the number of objects measured to correspond with the reduced accuracy of the resulting measurement, expected.

Finally, with 20 Carbon stars in the Sagittarius tidal tail, we could still measure the mass within 20 kpc and the shape of the Galaxy at that radius with accuracies of 10%.

Instrument and Operations Requirements

R_0 and the Shape of the Bar	Goal	Recommendation	Floor	Comments
Astrometric accuracy	4 μas (single star)	4 μas (single star)	10 μas (single star)	wide-angle
Star brightness	V = 16	V = 16	V = 16	Red Clump Stars
Number of Objects	150	50	20	
Measurement baseline	5 years	5 years	5 years	

Galactic Mass Distribution Using Tidal Tracers	Goal	Recommendation	Floor	Comments
Astrometric accuracy	2 μas (single star)	4 μas (single star)	10 μas (single star)	wide-angle
Proper motion accuracy	10 μas yr^{-1}	20 μas yr^{-1}	100 μas yr^{-1}	tidal tail width is 10 km/s
Star brightness	V = 17	V = 16	V = 16	Carbon Stars ($M_V = -2.5$)
Number of Objects	500	200	20	
Measurement baseline	5 years	5 years	5 years	

Halo Star Kinematics	Goal	Recommendation	Floor	Comments
Astrometric accuracy	2 μas (single star)	4 μas (single star)	10 μas (single star)	wide-angle
Star brightness	V = 16	V = 15	V = 15	
Proper motion accuracy	50 μas yr^{-1}	100 μas yr^{-1}	100 μas yr^{-1}	
Number of Objects	1000	400	100	
Measurement baseline	5 years	5 years	5 years	Parallax limited

Galactic Potential within 10 kpc (including V(R))	Goal	Require	Floor	Comments
Astrometric accuracy	2 μas (single star)	4 μas (single star)	10 μas (single star)	wide-angle
Star brightness	V = 16 K = 14	V = 15	V = 15	IR Capability would be helpful
Proper motion accuracy	50 μas yr^{-1}	100 μas yr^{-1}	120 μas yr^{-1}	
Number of Objects	1000	400	400	
Measurement baseline	5 years	5 years	5 years	Parallax limited

6.9 Orbits of Small Stellar Systems

Summary of Science Objectives

Globular clusters are one of the few classes of object that can be seen—and whose distances can be accurately determined—throughout the Galaxy. The spatial distribution and kinematics of the globular cluster system provide a powerful probe of the mass distribution of the Galaxy, the phase-space and metallicity distribution of the cluster system, the formation of the Galactic halo, and the evolution of the cluster system itself. Many authors, starting with Mayall, have analyzed the globular cluster system with these aims in mind (see Thomas 1989 and references therein). All of these analyses have used angular positions, distances and radial velocities—4 of the 6 phase-space coordinates. With this information it is possible to show that the phase-space distribution is approximately isotropic (i.e. uniform on the energy hypersurface) within the solar circle, but it is not possible to constrain strongly either the phase-space distribution outside the solar circle (in particular whether the orbits are isotropic or predominantly radial) or the Galactic potential (in particular whether the Galaxy has a massive dark halo).

Accurate proper motions can greatly enhance the power of such analyses by providing the final two phase-space coordinates. Ground-based proper motions are now available for ~ 25 of the ~ 200 Galactic globular clusters (Dauphole et al. 1996), about half of which have claimed errors < 1 mas/yr (corresponding to 50 km/s at 10 kpc); neither the number nor the accuracy of these measurements is sufficient to constrain strongly the kinematics of the cluster system.

The satellite stellar systems at > 20 kpc from the Galactic center (dwarf galaxies and distant globular clusters) constrain the mass and extent of the Galactic dark halo and offer insights into the formation of the Galaxy by gravitational collapse. The usefulness of these systems is limited if only radial velocities are available, as there is a degeneracy between the effects of a massive halo and a predominantly radial velocity distribution, both of which lead to large rms radial velocities. This degeneracy can be removed by proper motion measurements. Determining the proper motions of all of the satellites of the Galaxy to an accuracy of 5 km/s should be part of the Science Recommendations for SIM.

Science Goals

The issues raised above can all be addressed within what is currently viewed as the basic "requirements" of the Mission except for the matter of total throughput. The number of stars required per cluster can be kept to a minimum if an aggressive ground-based effort is used to establish membership. Even so, it is probably necessary to observe two members per cluster to be absolutely certain that binary motion effects are recognized. We set this as a goal.

Science Recommendations

Of ~ 150 known globular clusters, over 90% are within 30 kpc of the Sun (see Harris 1996). Measuring the transverse velocity of these clusters to a level of 5 km/s requires a proper motion accuracy of 35μas/yr. Only one (well established) member per cluster will be observed.

Almost all of the clusters have an adequate supply of red giant stars with $V < 18$. The exceptions are a handful of heavily reddened clusters near the Galactic center, and a few very distant clusters. The reddened clusters can be discarded from the sample without significant loss of information. The distant clusters are important for probing the mass and phase-space distribution at radii > 20 kpc, and will be discussed further below.

Kochanek (1996) lists 25 satellites of the Galaxy with Galactocentric radii between 20 and 250 kpc and known radial velocities (16 globular clusters, 8 dwarf spheroidal galaxies, and the Magellanic Clouds). Most of these are at distances < 140 kpc, except for the dwarf spheroidals Leo I and Leo II at 220 kpc. Determining the tangential velocity of Leo I and II to 5 km/s requires a proper motion accuracy of 5μas/yr. All of the inner dwarf spheroidals have stars at $V <$ 18–18.5, but the Leo galaxies and the distant globular clusters require reaching $V =$ 19.5–20.

Many of these observations do not require measurements over the whole 5-year mission lifetime to achieve the needed proper motion accuracies.

Science Floor

Determining the proper motions of $\sim$ 90% of the Galactic globular clusters to an accuracy of 5 km/s ($\sim$ 5%) should be part of the Science Floor for SIM.

Instrument and Operations Requirements

Summary for Small Stellar Systems

Nearby Globular Clusters	Goal	Recommendation	Floor	Comments
Proper Motion accuracy	35 μas yr^{-1}	35 μas yr^{-1}	35 μas yr^{-1}	Wide-Angle
Object Brightness (V)	16.0	16.0	16.0	
Number of Objects	200	100	100	

Distant Satellites & GCs	Goal	Recommendation	Floor	Comments
Proper Motion accuracy	5 μas yr^{-1}	5 μas yr^{-1}	N/A	Wide-Angle
Object Brightness (V)	20.0	20.0	N/A	$d >$ 100kpc
Number of Objects	20	10	N/A	
Object Brightness (V)	18.0	18.0	N/A	$d <$ 100kpc
Number of Objects	50	25	N/A	

6.10 Rotational Parallaxes of Nearby Spiral Galaxies

Summary of Science Objectives

This proposes direct measurement of the distance to nearby spiral galaxies, eliminating use of luminosity based distance indicators. It will provide a direct calibration of the Tully-Fisher relation used to measure larger distances in the universe. Luminosity calibrations of bright objects in a variety of external systems will then be available, including the full range of Cepheids and RR Lyra stars observable in nearby Spiral systems.

Late Type Galaxies Appropriate for Rotational Parallax Determination

NGC	Messier	Type	i deg	d Mpc	W(20) km/s	μ(M) μas/yr	μ(m) μas/yr	V(M$_V = -8.5$) mag
55		Sc	84	2.0	196	1	10	18.0
224	M31	Sb	77	0.77*	533	16	75	16.0
247		Sc	76	2.2	220	3	11	18.2
253		Sc	81	3.0	434	3	16	18.9
300		Sc	44	2.2*	163	8	11	18.2
598	M33	Sc	56	0.84*	192	16	29	16.1
3031	M81	Sb	57	3.6*	455	10	18	19.3
7793		Sd	47	4.1	193	5	7	19.6

*Distance from Freedman et al. 1994 and references therein.

Brief Statement of Technique

This technique rests on the near circular motions seen in the disks of intermediate to late type spiral galaxies. The measurement of proper motions of individual stars at several locations in the disk of a spiral galaxy, when combined with ground-based radial velocity measurements, can provide an independent measurement of the rotation curve at the location, the inclination of the disk and the distance. Some averaging is required to account for peculiar motions of the individual stars and the effects of warped disks and spiral arm structure. These will probably be the limiting systematic effects, but should not interfere with distance determinations to worse than 5% in the more massive systems.

Science Goal

The Goal is to obtain Rotational Parallaxes to every large spiral galaxy with individual stars bright enough to be within the observing limit of SIM. The ideal galaxy is one viewed at an inclination of 45° (so that there is a significance in both the proper motions modulations and the radial velocities). Nearly edge on systems can also be used but the inclinations, which enter weakly, will have to be estimated by other means. Face on systems will be limited by the accuracy of the radial velocities.

Therefore, assuming a limiting magnitude of V = 20 and noting that all but M31 and possibly M33 can be observed in small angle mode (it being differences in motions across the systems that are critical), the objects in the accompanying table should be observed to achieve the science goals.

In this tabulation we have used the compilations of Sandage & Bedke (1985, "SB"), Tully (1988), and Schmidt & Boller (1993) in estimating the various parameters. In addition to the NGC number Messier numbers (columns 1 and 2), the table provides the morphological type (column 3) from SB, the inclinations (average of SB and Tully - column 4), distance (from SB except where indicated; NGC253 is from Tully - column 5), the full H I velocity width at the 20% level (Tully - column 6) and the deduced annual proper motions alone the major (M) and minor (m) axes of the galaxies (column 7 and 8 respectively). Finally, column 9 gives the (unreddened) apparent magnitude of a star an with absolute visual magnitude of -8.5. Objects with prominent bars or obvious distortions from interactions with neighboring galaxies have been excluded.

The goal is to measure the distances of each of these to the limits set by systematic errors in the radial velocity measurements, assumed to be 10 km s^{-1}, or in the proper motions (small angle or large angle). For the closer systems, this is easily accomplished. However, for M 31 and M 33 we wish further to make the process wholly self-consistent, thereby avoiding as many systematic errors as possible. In these cases, SIM will need to determine the velocity curve through a range of radial distances as well as solve for the other parameters. Thus, for these two nearby systems we expect to observe 25 bright members in each quadrant over the range of distances where the rotation curve is nominally constant. For the other systems, 25 objects total, given guidance from existing rotation curves, should suffice to identify "run away" and other anomalous objects and achieve solutions accurate to 5% in distance (0.1 in magnitudes). The exception to this will probably be NGC 7793 with its relatively low rotation velocity.

These measurements all require the longest possible time baselines.

Science Recommendation

The science recommendation for the mission is defined as basically reducing some of the goals described in the Science Goal section, above. The observations described for M 31 and M 33 seem fairly modest and will be retained. We will assume M 106 and NGC 7793 are beyond the instrument's capabilities, owing to distance and the low transverse motions. NGC 55 and NGC 253 are essentially edge on ($\sin i \geq 0.98$), the inclinations can be taken from other sources with little effect on the distances and hence the distance can be obtained from the minor axis proper motions alone - 10 objects in the range $18 \leq V \leq 19$ observed over the mission should suffice. The remaining three objects, requiring observations of objects in the same magnitude range, will benefit from a more complete sampling, 25 objects each.

Science Floor

Even at a reduced capability level such as that associated with the Science Floor a distance to M 31, accurate to better than 10% and independent of all assumptions inherent in using luminosity calibrations, should be available. A distance to M 33 at about 10% should also be accessible. This would require a total accuracy of 5 $\mu\mathrm{as\,yr}^{-1}$ over the whole mission for twenty-five 16th magnitude objects, each.

Instrument and Operations Requirements

Rotational Parallaxes	`Goal`	`Recommend`	`Floor`	`Comments`
Astrometric accuracy				Note 1
M 31 & M 33	5 μas	5 μas	10 μas	Wide-Angle
NGC 55,247,253,300,&M 81	1 μas	1 μas		Narrow-Angle
NGC 7793	1 μas			Narrow-Angle
Measurement baseline	5 yr	5 yr	5 yr	
Star brightness (V)				
M 31 & M 33	16	16	16	
NGC 55,247,253,300,&M 81	18–19	18–19		
NGC 7793	19–20.5			
Number of Objects / galaxy				
M 31 & M 33	100	100	25	
NGC 55 & 253	25	10		
NGC 247,300,&M 81	25	25		
NGC 7793	25			
Proper motion accuracy				
M 31 & M 33	2.5 μas yr^{-1}	2.5 μas yr^{-1}	5μas yr^{-1}	
NGC 55,247,253,300,&M 81	0.5 μas yr^{-1}	0.5 μas yr^{-1}		
NGC 7793	0.5 μas yr^{-1}			

Note 1: These are mission accuracies for the narrow-angle measurements. The measurements needed are of proper motions, the position accuracies are derived.

6.11 Dynamics of the Local Universe

Summary of Science Objectives

Dynamics of the Local Group

Dynamical studies of the Local Group of galaxies provide our most detailed probe of the mass distribution and the development of structure in a typical collapsing group on 1 Mpc scales. Investigations of Local Group kinematics using radial velocities and distances have been conducted by Kahn and Woltjer (1959), Mishra (1985), Peebles (1996) and many others; in particular the Kahn-Woltjer study provided the first evidence for large amounts of dark mass in the Galaxy and M31. SIM will enhance the power of these studies not only by providing more accurate distances but more importantly by providing proper motions for a number of galaxies in the Local Group. Each such measurement means that all six phase-space coordinates of the galaxy will be known and these measurements combined with the age of the Universe and constraints from linear perturbation theory strongly overdetermine the orbit for a given mass distribution. Apart from nearby satellites of our own Galaxy, the most promising candidates include M31, M33, NGC 6822, IC 1613, WLM, and IC 10.

Dynamics of nearby galaxies

There are over 200 known galaxies outside the Local Group but within 5 Mpc. If, as most cosmologists assume, the peculiar velocities of these galaxies relative to the Hubble flow arise from gravitational instability, they reflect the initial perturbation spectrum and the distribution of mass in the universe. Proper motions are much more powerful probes of structure development than radial velocities because they are orthogonal to the Hubble expansion. A typical peculiar velocity of 100 km/s corresponds to $4\,\mu$as/yr at 5 Mpc.

Many of the nearby galaxies are clustered into groups. The main groups within 5 Mpc include IC 342, M81, NGC 4244, Cen A, Sculptor, and perhaps M101, but we shall concentrate here on the Sculptor group at roughly 2 Mpc. The dynamics of virialized groups can be used to probe the distribution of dark matter; the principal limitation to analyses of this kind is that redshift provides only one of the three velocity components of each galaxy. By measuring proper motions, SIM can determine the other two velocity components and thereby dramatically enhance our understanding of the orbits and masses in nearby groups.

Science Goals

Dynamics of nearby galaxies

The brightest stars at visual magnitudes in giant galaxies with recent star formation are late A or F-type supergiants with $M_V \simeq -8$; at 2 Mpc this corresponds to $V = 18.5$. At least 5–10 stars should be observed per galaxy to minimize contamination by internal motions. The brightest stars in smaller galaxies will be fainter, and early-type galaxies will not be measurable at all at this distance. A reasonable science goal is the measurement of proper motions of galaxies at 2 Mpc to an accuracy of ±10km/s; this in turn requires a proper motion accuracy of $1\,\mu$as/yr at $V = 18.5$. The scientific harvest from such observations will depend strongly on the proper-motion accuracy of SIM at its faintest limiting magnitudes.

Science Recommendations

Dynamics of the Local Group

The brightest stars in late-type galaxies at 1 Mpc have $V < 18$ and hence are easily measurable with SIM. A typical transverse velocity of 100 km/s corresponds to 20 μas/yr at 1 Mpc. Therefore such measurements do not challenge the requirements for SIM. The elliptical satellite galaxies of M31 (NGC 205, M32, and several dwarf spheroidals) cannot be measured by SIM since their brightest stars are too faint, although the central nucleus of M32 might be bright enough. Note that more extensive measurements of M31 and M33 are proposed in the section on Rotational Parallaxes.

Dynamics of nearby galaxies

As recommendations on the measurement of nearby galaxies, we reduce the fairly demanding faint magnitude limit to V=17.5, limiting the stellar measurements to the few objects that reach $M_V = -9$. This reduces the exposure times but likely the number of available objects as well.

Instrument and Operations Requirements

Sculptor Galaxies	Goal	Recommendation	Floor	Comments
Proper Motion accuracy	$1\,\mu$as yr^{-1}	$2\,\mu$as yr^{-1}	N/A	Wide-Angle
Object Brightness (V)	18.5	17.5	N/A	
Number of Objects[1]	125	50	N/A	

Local Group	Goal	Recommendation	Floor	Comments
Proper Motion accuracy		$2\,\mu$as yr^{-1}	N/A	Wide-Angle
Object Brightness (V)		18	N/A	
Number of Objects		40	N/A	Excludes M31 & M33

Comment:

Several objects included above are also included in the proposed project on Rotational Parallaxes, where the measurements will go well beyond what is required here. No account has been taken of that in these estimates.

6.12 Astrometric Gravitational Microlensing Events

Summary of Science Objectives

Similar to photometric microlensing, SIM can exploit astrometric signatures created in a microlensing encounter to infer physical properties of the source and lens. In particular, Boden et al (1998) demonstrate the application of simulated microarcsecond-class astrometry to reconstruct the mass and kinematic properties of the lens – something not currently possible with the vast majority of photometric-only detections. Additionally, Paczyński (1998) describes applications of the technique to measure the masses of individual stars (see also Hosokawa et al 1993, Miralda-Escudé 1996 and Paczyński 1996), and the measurement of stellar diameters (taking into account finite source-size effects, c.f. Mao & Witt 1998). Of the three of these projects, the study of halo lenses is probably the most important, and we will concentrate on it here.

Brief Statement of Technique

Because the positions and intensities of gravitational lens images evolve non-trivially in time in a microlensing encounter, microlensing (where by definition the lensing images are unresolved by the observer) produces both photometric and astrometric observables. Monitoring these observables over time yields an observable set that can be used to estimate lens and source parameters. While some parameters are amenable to narrow-angle techniques, SIM's wide-angle accuracy is sufficient to determine mass and distance for the vast majority of Galactic bulge and LMC/SMC events (Paczyński 1998, Boden et al 1998).

SIM cannot detect microlensing events a priori – instead it must rely on other mechanisms for event detection. The most straightforward strategy would be to key on events detected photometrically in wide-field surveys such as the MACHO and OGLE2 projects (or their successors). If this is indeed the case, the correct strategy would seem to be a combined reduction of both the photometric and astrometric data (see similar comments in Høg et al 1995) – examples and expected performance are outlined in Boden et al (1998). It also presumes that SIM can be tasked in a "target-of-opportunity" mode in a few (say 4) days, so as to service the event near photometric maximum where the astrometric motions are the most dynamic. Post photometric maximum this astrometry must span a roughly 3yr period to allow sufficient sampling of both the lensing event itself and the motions of the background source.

Science Goal

Mass, distance, and kinematic determinations for 15 LMC/SMC events and 20 Galactic Bulge events to $< 10\%$ accuracy in mass. Based on simulation results described in Boden at al (1998) this requires periodic astrometry at the ~ 5 μas level for V $\sim$ 19 LMC/SMC sources, and ~ 10 μas on V $\sim$ 16 Bulge sources. It also presumes that the events are photometrically detected and monitored during the photometric amplification.

Science Recommendation

Mass, distance, and kinematic determinations for 5 LMC/SMC events and 10 Galactic Bulge events to $< 15\%$ accuracy in mass. Based on simulation results described in Boden at al (1998) this requires periodic astrometry at the ~ 10 μas level for V $\sim$ 19 LMC/SMC sources, and ~ 15 μas on V $\sim$ 16 Bulge sources. It also presumes that the events are photometrically detected and monitored during the photometric amplification.

Science Floor

None.

Instrument Requirements

Galactic Bulge Events

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Distance	10 kpc			
Star brightness	V $\sim$ 14 – 17			
Einstein radius r_E	300 – 1000 μas			
Astrometric accuracy	10 μas	15 μas	N/A	
Mass error	10%	15%	N/A	
# Visits/Duration	30/3yr	30/3yr	N/A	
Number of Objects	20	10	N/A	

Operations Requirements

To service astrometric microlensing events SIM will need to be able to act on new detections in a target-of-opportunity mode, responding in a maximum of a few days to a new detection. During the peak of the photometric amplification the apparent astrometric motion is quite

LMC/SMC Events

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Distance	~ 50 kpc			
Star brightness	V $\sim 18 - 20$			
Einstein radius r_E	$50 - 500$ μas			
Astrometric accuracy	5 μas	10 μas		
Mass error	10%	15%	N/A	
# Visits/Duration	30/3yr	30/3yr	N/A	
Number of Objects	15	5	N/A	

dynamic, and it is important to sample the target frequently (e.g. every couple of days) during this period. Well after the peak of the photometric amplification the frequency of sampling can be greatly reduced (say once a month) for an extended period (say 3 yr), so as to establish the relative source-lens proper motion and source parallax.

6.13 The Extragalactic Frame Tie

Summary of Science Objectives

Global (wide-angle) astrometry establishes a coordinate system that is undefined by an arbitrary rotation. Many scientific programs are unaffected by this ambiguity, particularly those that depend on parallaxes. Alternatively, projects that depend on proper motions, particularly motions of objects well distributed across the sky, can not be effectively pursued unless limits can be placed on any remaining coordinate motions. Currently, the method of choice to remove these motions is to systematically observe a series of extragalactic objects, the more distant the better, with the assumption that transverse velocities will remain small on an all sky basis. We discuss here the limits imposed on residual motion in the coordinate system in order to achieve the scientific goals described above, and in order for SIM to contribute to the current international standard system.

The International Celestial Reference Frame

Astrometric data rely on observations made with respect to some reference system. In a case like SIM, the observations of the grid will define an instrumental reference frame. This frame will have an accuracy dependent upon the accuracy of the individual observations and the rigidity of the frame determined by the number of observations and the connections between the observations.

The observations from SIM will be used to construct a self-consistent instrumental reference system which will be internally more precise (and hopefully more accurate) than any previously existing system. This SIM instrumental system must then be adjusted to some external reference system. That adjustment takes the form of orientation at some epoch and elimination of any rotation with respect to an inertial, or extragalactic reference frame.

The current most accurate reference system is the International Celestial Reference

System (ICRS), which is realized by Very Long Baseline Interferometry (VLBI) and designated the International Celestial Reference Frame (ICRF). Measurements are made of a base set of ExtraGalactic Objects (EGOs) (mostly Quasars, BLLac objects, and some AGNs). EGOs provide "benchmarks" which are so far away that their expected proper motions, due to their transverse motion, should be the smallest observable of any objects in the universe. However, the physical changes in the structure of the EGOs in the radio and optical wavelengths will be the ultimate limitation to determining a non-rotating reference frame. The current best positions are good to better than a milliarcsecond. Current estimates are that the positional and rotational knowledge of the ICRF system is better than 200 microarcseconds.

SIM must make observations for the derivation of the extragalactic tie. EGOs brighter than 20th magnitude must be observed over the life of the mission in order to determine the orientation and rotation of the SIM grid with respect to the ICRF. As with VLBI, the level of accuracy is expected to be limited by internal structure within the EGOs at the microarcsecond level and because of the difficulties in finding enough bright objects, well distributed on the sky, to provide the "benchmarks" to tie in the whole SIM reference frame.

If SIM centroids of EGOs are good and stable at the 1 microarcsecond level, then the system stability will depend on the stability of the grid lockup and the accuracy of relative measurements within a tile. If SIM centroids of EGOs move around and/or are fuzzy at the 50-100 microarcsecond level, then each EGO will contribute a large error to the total error budget of the reference frame tie.

The astrometric projects FAME and GAIA will be going through the same extragalctic reference frame tie process as SIM, and should provide optical observations of positions and proper motions of many sources at 1 to 50 microarcseconds accuracy at different epochs. These observations, including their ties to the ICRF, will provide tests of the orientation and rotation of the SIM reference frame.

If SIM's measuring accuracy and grid lockup errors are under 10 microarcseconds, then SIM could provide a global reference system that would be a standard for other interferometric and astrometric missions and programs, SIM would provide the most accurate reference frame for the future.

At a minimum, SIM should attempt to at least meet (and thereby independently verify) the level of reliability currently being approached in the ICRF determined from VLBI, $100\,\mu$as. Over a 5 year mission, this implies determining the positions to (TBD) EGOs to that accuracy, or, equivalently, putting $50\,\mu$as upper limits on any systematic proper motions during that time.

The Science Topics

In addition to reference frame issues, SIM must provide an approximation of an inertial frame in order to produce reliable results for the topics described earlier. The topics that place the most demands on the residual rotation of the SIM frame are Galactic Structure and related studies and extragalactic Rotational Parallaxes.

Galactic Structure Studies Absolute motion must be known for any studies involving space velocities. For the proposed galactic studies (§ 6.8), the absolute motions are required to $100\,\mu\mathrm{as\,yr}^{-1}$ as a Floor. The contribution to the error from the absolute frame error should be a small fraction of the total error. The motions of the system of Globular Clusters requires a Floor accuracy of absolute motion of $35\,\mu\mathrm{as\,yr}^{-1}$ (§ 6.9). Therefore, the requirement on the knowledge of the system motion, $20\,\mu\mathrm{as\,yr}^{-1}$, will be a major contributor to this error budget. Since, this is a systematic error, $20\,\mu\mathrm{as\,yr}^{-1}$ is a hard upper limit.

Motion in the Globular Cluster system again sets the most stringent demands for the Recommendations at $5\,\mu\mathrm{as\,yr}^{-1}$. For a Goal, we require that the systematic offset from an undetected rotation be less than other errors by a factor of 2.

Rotational Parallaxes The recommended accuracy for motions in the rotational parallax project is $2.5\,\mu\mathrm{as\,yr}^{-1}$ with a Floor requirement of $5\,\mu\mathrm{as\,yr}^{-1}$. Because we are looking for the rotation of a stellar system, the absolute motions of the target stars are immaterial except as they introduce spurious rotations due to the system rotation. The worst case occurs when the pole of the residual rotation of the system lies at the center of the galaxy whose rotation is being measured. The error of the system rotation in $\mu\mathrm{as\,yr}^{-1}$ translates directly into an inferred rotation whose value is the system rotation times the sine of the individual target distance from the pole (in this case the center of the galaxy being measured). Note that the sine changes sign as one crosses the pole of rotation.

Since the system rotation must be known to better than $5\,\mu\mathrm{as}$ as a floor requirement, we need to look at the maximum extent of the galaxy around the residual pole of rotation. For M31, that extent is of the order of 2 degrees (1/30th of a radian), so that the contribution from an error in the system rotation is $20\sin(1/30)$ or $2/3\,\mu\mathrm{as\,yr}^{-1}$. For rotational parallaxes, the $20\,\mu\mathrm{as\,yr}^{-1}$ absolute proper motion accuracy meets the floor requirements and even the mission recommendations ($2.5\,\mu\mathrm{as\,yr}^{-1}$).

Target Complexity

In estimating the number of objects it is necessary to assume that both the number of bright EGOs available will be increased and that the basic stability of the average EGO will be better for the Recommendations compared to the Floor. The assumed improvement is a factor of 4 in each case. At this point these are guesses. The final state of the EFT and the average stability of the average EGO will probably not be known until after the mission.

Instrument and Operations Requirements

Summary: Extragalactic Frame Tie

	Goal	Recommendation	Floor	Comments
Proper Motion accuracy	$5\,\mu\mathrm{as\,yr}^{-1}$	$5\,\mu\mathrm{as\,yr}^{-1}$	$35\,\mu\mathrm{as\,yr}^{-1}$	Wide-Angle
Object Brightness (V)	17.0	17.0	16.0	
Number of Objects	100	100	20	TBD

7 SRD: Synthesis Imaging and Nulling Requirements

7.1 Background

The design requirements which permit SIM to attain its enormous astrometric accuracy also make SIM a powerful instrument for mapping high-brightness targets by synthesis imaging at optical wavelengths. SIM offers the prospect of making diffraction-limited images on high-brightness targets with the equivalent of a 12-meter optical telescope in space. This is a fundamentally new capability for astronomy, and one which is unique to SIM.

SIM's astrometric goals can be achieved by measuring a few parameters (two coordinates and an intensity) on each target. The astrometric science programs are characterized by measurements on large numbers of structurally-simple stellar targets which are observed briefly but repeatedly during the mission lifetime in order to determine positions, parallaxes, and proper motions.

Imaging extends SIM's capability in another direction, in a sense somewhat orthogonal to astrometry on simple stellar targets. In imaging, the goal is to map in quantitative detail the distribution of surface brightness in *complex* targets. This capability opens up many new areas of research for SIM, corresponding to the many different types of complex targets we know exist in astronomy. These targets include not only dense groupings of many stars, but also extended distributions of line and continuum emission emanating from a whole variety of non-stellar targets ranging from circumstellar nebulae to jets in the nuclei of nearby galaxies.

The discovery space which can be covered with SIM in its imaging mode is therefore potentially very broad, and it is not possible for us to provide here a complete inventory of all programs which fall into that space. We have instead analysed several programs which are sufficiently representative to span this discovery space. Using computer modelling, we have distilled from these programs the relevant additional instrumental requirements for SIM beyond those already demanded for high-precision astrometry. Briefly, the main additional requirement is to design SIM so as to provide a full and complete range of interferometer baselines.

7.2 Imaging and Nulling-Imaging Science with SIM

The science goals for which SIM offers unique capabilities involve high-surface-brightness targets which in most cases have already been imaged to the limit of HST resolution. In Table 7.2 we list 6 different classes of such high-surface-brightness targets for which SIM will provide unique new information in imaging and nulling-imaging mode.

In the following sections we analyse the requirements for the imaging of proto-planetary disks and galactic nuclei in more detail. The instrument requirements for these projects turn out to be representative of all SIM imaging science projects, and in addition they represent two subjects of intense interest at the present time.

Representative Imaging Science with SIM

Topic	Prototype	Typical Max Brightness	Key Questions
Protoplanetary disks	β Pic	13.5 mag/$\square''$in V	see section 7.3 for details
Nuclear regions of nearby normal galaxies	M31, M32	13.5 mag/$\square''$ in V	see section 7.4 for details
Nuclear regions of nearby active galaxies (emission lines)	NGC 1068, M87	$> 2 \times 10^{-13}$ ergs/cm^2/s/$\square''$	see section 7.4 for details
Young star clusters in interacting galaxies	NGC 4038/39	$<$ 15 mag/$\square''$ in V	Are these young globular clusters?
Winds of Wolf-Rayet stars	Gamma-2 Velorum	$<$ 9 mag/$\square''$ in V, nulling mode, line & continuum	What drives these winds? How is carbon dust made in such great quantity?
Dense stellar clusters	R136, NGC3603	$<$ 7 mag/$\square''$ in V (crowded fields)	Is mass segregation from initial conditions or a result of evolution? How massive is the most massive star? Are blue stragglers formed by mergers? Do these clusters harbor black holes?

7.3 The AU-Scale Structure of Protoplanetary Disks, and Planet Formation

SIM will have an entirely new capability with the nulling beam combiner which is to be included in the design. It is possible to use the data provided by this channel to make images, a mode we call "nulling-imaging". This mode, coupled with the extremely high spatial resolution available with SIM, provides a unique new capability for obtaining detailed maps of dust disks on the AU scale around stars as distant as 1 kpc from the sun, including examining the occurrence of "gaps" in the inner parts of these disks. Such gaps in protoplanetary disks may be tracers of planet formation (e.g. Dermott et.al. 1998, although the dynamical basis is complicated, e.g. Goldreich & Tremaine 1980). The frequency of occurrence and the distribution of dust disks around main sequence stars is of considerable interest to the Terrestrial Planet Finder (TPF) project (e.g. Backman et.al. 1998), since such disks will compromise the ability of the TPF to directly detect earth-like planets.

A key question confronting researchers of exozodi disks is to understand the relationship of the disk structure to the age of the associated star (Backman & Paresce 1993; Lagrange, Backman, & Artimowicz 1999). What fraction of stars have these disks? How does the disk density scale with the age and luminosity of the star? What is the evolutionary time scale of these disks?

β Pic (Smith & Terrile 1984) is a spectacular and well-studied example of such exozodi disks. The central star appears to have arrived on the main sequence, but is probably very young; its estimated age of $\sim 50 \times 10^6$ yr (Lagrange, Backman, & Artimowicz 1999) is only a few percent of the lifetime of a mid-A star, so only a similar fraction of potential field star targets would be so young. More mature (and thus less dense) debris disk systems such as those around Fomalhaut and Vega with ages in the few $\times 10^8$ yr range ought to be much more common. A rough estimate would be that 30-50% of all main-sequence A stars could have exozodi disks at the level of Vega's disk, which has about 1/100 of the optical depth of β Pic's disk, and is about 4×10^8 yrs old. This is consistent with results from recent ISO surveys of nearby stars (e.g. Dominik et al. 1998).

The strategy, then, would be to image main sequence stars in clusters (A stars, but also other spectral types for comparison); cluster membership gives the age of the central star, SIM imaging gives the density, size, and in denser cases the structure of the disk. One would pick clusters in the age range $10^7 - 10^9$ yr, spanning the epoch of "planet construction" (Lissauer 1993) and subsequent heavy bombardment (Gaidos 1999) in our solar system. SIM has the ability to dramatically increase the available sample in this important age range.

Simulations of exozodi disk observations with SIM carried out by Böker & Allen (1998, 1999) show that, in nulling-imaging mode, SIM can map in detail the exozodi disks which are 1/10 of the brightness of β Pic, surrounding stars as distant as 1 kpc from the sun. With further optimization of the image reconstruction method, detections of systems as faint as 1/100 of β Pic will be possible. The problem will be to establish the target list, since at distances of 1 kpc there are not yet sufficient numbers of IR-excess objects known. Here is an opportunity for synergy between SIM and SIRTF, with SIRTF supplying the target list for SIM nulling-imaging.

All exozodi systems we have been able to study in sufficient detail with HST (e.g. β Pic, HD141569 - Augereau et al 1999 and Weinberger et al. 1999 - and HR4796A - Jayawardhana et al. 1998 and Koerner et al. 1998,) show "rings" or "collars" which are at large distances from the parent star compared to the expected size of the planet-forming zone. These distances correspond to the Kuiper belt around the sun; HST observations can not penetrate closer to the star, down into the terrestrial planet zone. For the brighter disks, SIM will provide key information on the origin of these inner gaps in exozodi systems. Are these indicative of the ice sublimation point, i.e. dependent on the luminosity of the central star, or are the gaps created by dynamical processes of "planet-sweeping"? The answers here lie in the structure of the inner edges of these gaps; smooth edges are likely to be caused by ice sublimation, whereas sharp edges probably signal dust and have a dynamical origin in processes connected with planet formation. A tantalizing clue has been provided by the ground-based coronagraphic observations of β Pic by Golimowski, Durrance, & Clampin (1993) (see also Burrows & Krist 1996), who detected changes in the structure of the disk at a radius of ~ 100 AU which may be related to these processes.

Summary of Science Objectives

SIM's 8 milli-arcsec resolution (with a 10-meter maximum baseline) corresponds to 8 AU at a distance of 1 kpc, so that solar-system-sized regions around the nearby stars are open to detailed study with SIM. The nulling capability permits us to suppress the light from an adjacent bright star, which would otherwise contribute too much photon noise to realize the full continuum detection sensitivity threshold. The price for this feature is that the images are always symmetric about the field center, but this is quite tolerable for accretion and dust disks around stars since such symmetry is expected. For instance, two-armed symmetric spiral wave instabilities in gas and dust disks would be accurately rendered. Table 7.3 summarizes the properties of this class of targets in terms of prototypical objects; these prototypes have been studied to the limit of HST resolution.

Protoplanetary disk imaging targets

`Topic`	`Prototype`	`Typical Max Brightness`	`Key Questions`
Dust disks around young main sequence stars	β Pic, HD141569, HR4796A	12 - 15 mag/$\square''$	What are the radial surface brightness distributions and how do they arise? How frequently do they show gaps, rings, or other features which may signal the presence of (forming) planets?
Young Stellar Object disks	GM Aur	$\sim$ 15 mag/$\square''$	Are central holes common, and how are they related to the way stars form from disks?

Science Goals

As a nearly-unexplored area representing the tip of one of the most critical new fields of astronomical science in decades, appropriate goals would be to establish the time scale for disk formation and dissipation, the frequency of disks, and the extent to which complex radial structure is present in the disks indicative of sweeping by forming planets. This would involve an extensive study of A dwarfs in clusters representing a range in ages (50) and a representative survey of both nearby A dwarfs and G dwarfs ($V \lesssim 6$) (200). Those that show disk signatures on a quick look should be imaged in nulling mode to full resolution (30). A representative sample of bright T Tauri objects ($V \lesssim 12$) showing evidence for disks should be fully null-imaged (20). The deep imaging in particular would benefit from additional dynamic range, showing better the nature of any gaps in the disks.

Science Recommendations

The science recommendation is to establish the frequency of occurrence and the shapes of dust disks (including the presence of inner rings or gaps), only at somewhat lower significance. At present we have images of only a few such systems, so we do not even know how large the discovery space can be. A significant sample of targets therefore needs to be observed. We therefore take as a recommendation that SIM will:

- Survey a sample of 20 A stars of varying ages in Galactic clusters in search of exozodi disks. The candidates will be taken from lists of the most promising objects available at the time of observation (presently such a list would consist of stars showing far-IR excess).
- Image in detail 10 bright dust disks whose spectral signatures show the presence of disk-to-gap transitions in the range accessible to SIM in order to determine the origin of these transitions.

SIM in its nulling-imaging mode is truly a unique new tool for launching a full-scale attack on questions of the nature and frequency of exozodi disks and their relation to the formation of planets around main-sequence stars.

7.4 The Parsec-Scale Structure of the Central Regions in Nearby Galaxies

In its imaging mode, SIM will enable major breakthroughs in the study of the extreme conditions which occur in the nuclei of galaxies. Normal galaxies and active galaxies are both prime targets.

Normal Galaxies

Our understanding of the nuclei of normal galaxies has been revolutionized with HST. We now know that (e.g. Faber et al. 1997):

1. all galaxies have power-law stellar density cusps near their centers, rather than homogeneous cores; and
2. the cusp slopes and central densities correlate with galaxy luminosity.

What drives these observed characteristics of galaxy nuclei remains unknown. Dissipation during galaxy formation (Mihos & Hernquist 1994), galaxy mergers (Faber et al. 1997), and black-hole-induced density cusps (van der Marel 1998) are all possibilities.

Some galaxies show double nuclei at HST resolution, e.g., M31 and NGC 4486B (Lauer et al. 1993, 1996), the nature of which is still a puzzle. For instance, one of the double nucleii of M31 contains a blue, barely-resolved structure (Lauer et al. 1998; Kormendy & Bender 1999) which may indicate the location of a massive black hole (Tremaine 1995). Possible models for this structure include a cluster of several early-type stars (or merged stars) with the brightest member at 21 mag in V. Simulations of SIM imaging observations of this model have been carried out by Böker, Allen, & Rajagopal (1999). These simulations show that it will be possible not only to identify the nature of these sources, but to measure their proper motions over the mission lifetime, thereby providing an independent and very specific test of the massive black hole model.

Active Galaxies

A few percent of all galaxies have active nuclei (AGN). The spectacular energy output from these systems has made them a topic of primary interest in modern astronomy (e.g., Peterson 1997). The observed narrow and broad optical emission lines have been attributed to rapidly moving gas close to a central black hole. However, the origin, kinematics and physical conditions of this gas have remained very much a mystery, due to a lack of spatially resolved information. HST has allowed the outer-parts of the narrow-line regions (NLR's) in nearby active galaxies to be resolved for the first time, yielding e.g. spectacular imagery of an ionization cone in NGC 1068 (Evans et al. 1993). In other galaxies, e.g., M87 (Ford et al. 1994) and NGC 4261 (Ferrarese, Ford & Jaffe 1996), stable disks of gas and dust yielded the first direct evidence for accretion disks around black holes. SIM can image these regions with parsec-scale resolution for the very first time, both in the continuum and in spectral lines, thus providing essential new information on NLR structure and physics, accretion disks, and the feeding of black holes. Simulations have shown (Allen & Böker 1998, Böker & Allen 1999) that even with modest spectral resolution (≈ 150), SIM can map the distribution & kinematics of the ionized gas in the vicinity of a massive black hole with high accuracy. If a higher-resolution capability (≈ 1000) is available on SIM, then not only the distribution but also the detailed kinematics of gas flows throughout the entire NLR can be determined. The physics of ionized knots on the parsec scale could be probed; one immediately gets an emission measure of a knot (from Hα) and hence a density if the size is known. This is relevant to the multi-phase structure of the NLR. [SII] densities and [OIII] temperatures would be interesting from the perspective of shock ionization. SIM imaging could resolve the current controversy about the source of the ionization (e.g. Wilson 1997); is it UV radiation from the central black hole engine or photons from large-scale jet-driven shocks?

The Narrow Line Regions of AGNs is also a topic for which an important synergy can be realized between optical imaging with SIM and radio imaging with the Very Long Baseline Array (VLBA). The radio and optical emission from the NLRs of AGNs are very closely connected (e.g. NGC1068; Gallimore, Baum, & O'Dea 1996, 1997), undoubtedly because the radio jets drive radiative shocks into the ISM, with subsequent cooling and increase of density. It will be extremely valuable to explore this connection down to the pc-scale with SIM. The VLBA provides about 5 mas resolution at 20 cm, quite similar to SIM. Because the VLBA measurements are phase-referenced to a nearby compact radio source, and this compact radio source is often a quasar (or a galaxy with a compact optical nucleus), observations of both the galaxy nucleus and the phase-reference source should allow precise registration of the optical and radio images.

Summary of Science Objectives

SIM will permit imaging the complex high-brightness central regions of nearby galaxies with more than 6 times the resolution of HST. SIM's 8 milli-arcsec resolution at 500 nm corresponds to 1.2 parsec at a distance of 30 Mpc, rendering the nuclei of all the nearby galaxies open to a degree of detailed scrutiny far beyond what has been possible up to now. Imaging can be done in the usual optical continuum bands (for the starlight) as well as in narrow bands suitable for measuring the kinematics and distribution of line emission.

Table 7.4 summarizes examples of specific prototypes in this subject area and some of the key questions pertaining to them which SIM can address. The prototypes have all been studied to the limit of HST resolution.

Imaging the nuclei of galaxies with SIM

`Topic`	`Prototypes`	`Typical Max Brightness`	`Key Questions`
Nuclear density cusps in normal galaxies	M32	12 mag/□″, stellar continuum	How far into the center does the light cusp go? Result of dissipation, galaxy merging, black holes? Implications for galaxy formation and evolution?
Multiple nuclei in normal galaxies	NGC 4486B, M31	14.3 mag/□″, 13.5 mag/□″, stellar continuum	Origin? Galactic cannibalism, merging black holes? How do they evolve?
AGN Narrow-Line Regions, Nuclear emission-line disks	NGC 1068, NGC 4261, M87	$> 2 \times 10^{-13}$ ergs/cm^2/s/□″, Hα, [SII], [OIII] emission-line imaging	What is the geometry and kinematics of the NLR gas? How did it get there? How is it related to the central black hole?

Science Goals

Since it appears that there will be no instruments of comparable imaging resolution in the visible for the foreseeable future, and considering that the possible synergy with the VLBA effort is so potentially rewarding, the goal for SIM imaging science should be a major survey of bright galactic nucleii (~ 400). Those showing compact structure (~ 80) would then be re-observed at full spatial resolution and moderate spectral resolution ($R \sim 100$). Further, select systems with strong nuclear H_α emission (~ 20) would be re-measured at full spatial resolution and higher spectral resolution ($R \sim 1000$).

Science Recommendations

The science recommendation is to determine the structure of the light distributions and the geometry and kinematics of the ionized gas in the nuclear regions of a small sample of nearby galaxies. We will choose 10 normal galaxies to be observed in continuum emission, and 10 active galaxies to be observed in line emission. The specific choice of targets will be made closer to the SIM launch date in order to take advantage of the latest information, e.g., from the Advanced Camera for Surveys (ACS) which will installed on HST in 2000. The minimum science recommendation is therefore that SIM:

- Image a first sample of 10 nuclear regions of nearby normal galaxies in the continuum; and,

- Image a second sample of 10 nearby Active Galaxies with emission-line gas using modest spectral resolution ($\approx 100 - 200$).

In its imaging mode, SIM will provide a unique capability to increase our knowledge of the physics of the nuclear regions in galaxies, thereby contributing to our understanding of the origin and evolution of galaxies themselves.

7.5 Common Instrument Requirements

This Section describes the instrument requirements for rotational synthesis imaging derived from the simulations of the two proto-typical targets described above: galaxy nuclei and dust disks. These requirements are common to both "direct" imaging and nulling-imaging.

In general, in order to provide an image which is accurate and reliable, the instrument must make measurements of the full range of structure which is present in the field of view, and the imaging process must not introduce spurious structure which is not present in the field of view. In order to do this, the instrument must be capable of providing adequately-calibrated complex visibility data (amplitudes and phases) for a sufficient range of interferometer baselines and orientations so as to permit a reliable and substantially distortion-free reconstruction of an arbitrarily-complicated distribution of brightness over the whole field of view defined by the focal plane aperture stop. In the following sections we attempt to quantify these terms.

The distortions can be expressed in terms of the *dynamic range* and the *image fidelity* which can be obtained in the reconstructed image:

- *Dynamic Range* refers to the *presence* of structure (often at the resolution limit) in the reconstructed image which actually is not present in the source;

- *Image Fidelity* refers to the *absence* of structure (often extended over the field) in the reconstructed image which actually is present in the source.

The dynamic range of a reconstructed image can be determined from that reconstructed image itself, and can often be improved by more sophisticated computer processing of the existing data set, at least down to the noise level. However, improvements in image fidelity require the acquisition of additional data at interferometer baselines which were missing in the initial observations.

Dynamic range and image fidelity are not easily specified in terms of purely instrument or mission requirements. They are a function not only of the instrument, but also of the complexity of the field being mapped. Factors affecting the dynamic range and image fidelity include:

- Instrument calibration

- The baseline coverage in the aperture (u, v) plane

- Signal-to-noise ratio of the complex visibility data

- Data weighting in the (u, v) plane

- Effectiveness of the reconstruction algorithm (from (u, v) data to the image)

The specification of the instrument parameters which affect dynamic range and image fidelity require computer modelling of different source distributions and an exploration of the relevant parameter space. We have done this for three representative model source distributions:

- the dense core of a globular cluster (Böker 1998);
- an ionized accretion disk surrounding a black hole in the nucleus of a nearby elliptical galaxy (Allen & Böker 1998); and,
- a protoplanetary dust disk surrounding a nearby star (Böker & Allen 1998).

The latter two topics are explored in more detail in Böker & Allen 1999.

Minimum Surface Brightness Sensitivity

The simulations show that the minimum surface brightness for which reliable imaging can be done must reach:

- 0.3 mJy/$\Box''$ in the continuum, averaged from 500 - 800 nm wavelength (this is $\approx$ 17.7 mag/$\Box''$ at V), and
- 2.5×10^{-14} ergs/cm^2/s/$\Box''$ in an emission line lying within a 4 nm instrumental passband at $\lambda = 650$ nm.

A full synthesis image to the specified sensitivity level must be achievable in 4 - 10 hours of on-target integration time, during which 150 - 200 different baseline separations and orientations must be observed. The continuum imaging sensitivity must be obtainable even in the presence of V $>$ 12 mag stars located anywhere in the focal plane aperture stop by using the nulling beam combiner. In this case the reconstructed images may be symmetric, appropriate for data in which the fringe phase is set to zero at all spacings.

These sensitivity requirements in turn require that the interferometer light-collecting elements have diameter ≥ 0.3 meters.

General Requirements

The general instrument requirements which flow from the simulations on the three different classes of targets are:

- It is desirable to be able to collect complex visibility data at any arbitrary point in the (u, v)-plane, i.e. at any baseline length and orientation. This requirement may be relaxed to apply to a finite number of points such that any position (including the origin) in the (u, v)-plane is less than a specified distance from one of these points. This may e.g. apply to "lock-down" positions of the interferometer elements. The maximum allowable distance D_{ld} between such lock-down positions along a one-dimensional truss is determined by $D_{ld} \leq \lambda / d_s$, where D_{ld} is the distance between lock-down positions and d_s is the diameter of the aperture stop in the focal plane. For instance if d_s is $0.1''$, then $D_{ld} \leq 103$ cm for $\lambda = 500$nm; for $d_s = 0.2''$, the sampling needs to be twice as dense, with $D_{ld} \leq 52$ cm.

- The dynamic range ought to exceed 100. That is to say, except for photon noise, the amplitude of the brightest spurious feature on the reconstructed image must be no more than 1% of the brightest real feature. This translates into a requirement for *consistency* in the calibration between sample points in the aperture plane at a level of 1% in fringe amplitude and 8° in fringe phase. This in turn puts a requirement on the *repeatability* of the pointing of the focal plane aperture stop on the sky at a level of TBD (but typically 10 milliarcsec for a stop of diameter $0.3''$).
- In imaging mode, individual visibility measurements from the science interferometers will typically have low signal-to-noise ratios (S/N), even though the image resulting from a reconstruction of a complete set of visibilities will have ample S/N. Hence, it is important that on-board processing of the data should not require any minimum value of detected signal strength before data is accepted for storage and downlink.
- Editing of imaging data in the ground processing is not generally expected to be possible based on the data itself. This is due to the fact that the S/N for an individual visibility measurement in imaging mode will in general be too small to detect bad data based on an analysis of that same data. As a means of detecting possibly-corrupted visibility measurements, engineering data for the spacecraft therefore needs to accompany each visibility measurement in the down link and post-processing. Flags should be set to indicate whenever any of the spacecraft sub-systems were out of nominal range.
- Imaging and nulling-imaging ought to be possible over the entire lifetime of the mission.

7.6 Table of Instrument Requirements

The instrument requirements derived from the simulations are summarized in the following tables. Note that the capability for imaging and nulling-imaging is required throughout the entire SIM mission lifetime.

Requirements Summary, Nulling-Imaging

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Continuum sensitivity (mJy/□″) (Note 1)	0.3	0.6	N/A	averaged over 300 nm bandwidth
Emission line sensitivity (10^{-14} ergs/cm^2/s/□″) (Note 1)	1.0	2.5	N/A	integrated in 5 nm channel bandwidth
Image dynamic range (Note 2)	250:1	100:1	N/A	
Spectral Coverage (nm)	400 - 1200	450-900	N/A	
Largest baseline (m)	≥ 12	10	N/A	resolution
Shortest baseline (m, Note 4)	0.5	1.0	N/A	image fidelity
Baseline increment (m, Note 4)	0.5	1.0	N/A	unaliased field
Number of independent observed (u, v) points	400	150	N/A	sensitivity, image fidelity, dynamic range
Total observing time	≤ 4 hr	≤ 10 hr	N/A	
Fringe amplitude calibration consistency (Note 3)	0.4%	1%	N/A	dynamic range
Nulling depth for point sources	10^{-5}	10^{-4}	N/A	
Number of nulling-imaging target fields	300	50	N/A	

Note 1:	Faintest brightness level in the image for reliable measurement.
Note 2:	After computer image restoration.
Note 3:	Relative to other sample points in the (u, v) plane.
Note 4:	Tolerance ±10%

Requirements Summary, Imaging

`Parameter`	`Goal`	`Recommendation`	`Floor`	`Comment`
Continuum sensitivity (mJy/□″) (Note 1)	0.3	0.6	N/A	averaged over 300 nm bandwidth
Emission line sensitivity (10^{-14} ergs/cm^2/s/□″) (Note 1)	1.0	2.5	N/A	integrated in 5 nm channel bandwidth
Image dynamic range (Note 2)	250:1	100:1	N/A	
Spectral Coverage (nm)	400 - 1200	450-900	N/A	
Spectral Resolution ($\lambda/\Delta\lambda$)	1000	100	N/A	
Largest baseline (m)	≥ 12	10	N/A	resolution
Shortest baseline (m, Note 4)	0.5	1.0	N/A	image fidelity
Baseline increment (m, Note 4)	0.5	1.0	N/A	unaliased field
Number of independent observed (u, v) points	400	150	N/A	sensitivity, image fidelity, dynamic range
Total observing time	≤ 4 hr	≤ 10 hr	N/A	
Fringe amplitude calibration consistency (Note 3)	0.4%	1%	N/A	dynamic range
Fringe phase calibration consistency (Note 3)	4°	8°	N/A	dynamic range
Number of imaging target fields	500	20	N/A	

Note 1: Faintest brightness level in the image for reliable measurement.
Note 2: After computer image restoration.
Note 3: Relative to other sample points in the (u, v) plane.
Note 4: Tolerance ±10%

8 SRD: Summary of Floor Requirements

The Science Floor is a statement of the minimum science which SIM must accomplish, if SIM is to be viable as a scientific mission. By definition (Section 4.4), the Science Floor lies below the level of instrument and mission performance required for the minimum science capability of some topics. The Floor is therefore a subset of the instrument and mission requirements in the previous Sections of this SRD. It was derived after lengthy discussions by the SIM Science Working Group and SIM Project members.

8.1 Science Floor Topics

Science Floor topics are summarized below. These topics all require astrometric accuracy. None requires imaging or nulling capabilities. All can be achieved with observations only in the optical band. Where specified, astrometric accuracies (in parentheses) are those of stellar parallaxes or proper motions from data acquired using repeated measurements **throughout the entire mission** (narrow angle measurements excepted):

- Detect planets with **2-20** Earth masses around 20 nearby stars (§6.3). A related requirement will be to detect giant planets or brown dwarfs of **20** earth masses to **80** Jupiter masses around 200 nearby stars (§6.4). (**3 μas, narrow angle - single measurement, 5 yr mission lifetime**)
- Determine stellar masses to 3% accuracy in 75 nearby binary systems (§6.5). **(50 μas)**
- Measure the distance to the 29 Cepheid members of nearby clusters and associations with 2% accuracy as well as several upper main sequence members of those systems, 150 objects (§6.6). **(30 μas)**
- Determine the distances to globular clusters with 6% accuracy up to distances of **6 *kpc*** (§6.7). **(10 μas)**
- Measure the distance to the center, the outer rotation curve, and other basic properties of the Galaxy (§6.8). **(10 μas, V=16)**
- Determine the proper motions of the nearby 100 Globular Clusters to 5 km s^{-1}(§6.9). **(35 μas yr^{-1}, V=16)**
- Determining the distance to M31 and M33 to 10% using Rotational Parallaxes (§6.10). **(10 μas yr^{-1}, V=16)**
- Tie the astrometric grid to the extragalactic frame using quasars (§6.13). **(20 μas yr^{-1}, V=16)**

To summarize, the Science Floor requires:

- a **limiting stellar magnitude** of V = 16,
- a **parallax/position** accuracy **(wide angle, mission)** of 10 μas,

- a **position** accuracy **(narrow angle, single measurement)** of 3 μas,
- a **proper motion** accuracy **(wide angle, mission)** of 10 μas yr^{-1}, and
- a 5-year **mission lifetime**.

9 SRD: Summary of the Science Requirements

The following tables summarize the Science Goals, Recommendations, and Floors for the SIM instrument.

9.1 Overall System Requirements

`Parameter`	`Goal`	`Recommend`	`Floor`	`Drivers`	`SRD Section`
Observational bandwidth, μm	Visible & near-IR: 0.4 - 2.2	Visible: 0.4 - 1.0	Visible: 0.4 - 1.0		6.1, 6.1
Target viewing accessibility	$\geq$ 6 months	$\geq$ 6 months	$\geq$ 6 months	Note 1	6.1
Sky coverage within a year	4π steradians	4π steradians	4π steradians		6.1
Mission lifetime (from end of verification phase)	10 years	5 years	5 years		6.1
Minimum continuous viewing period	20 minutes	10 minutes	5 minutes	Note 2	6.1
Target of opportunity response time	$\leq$ 2 days	$\leq$ 4 days	$\leq$ 10 days		6.12

Note 1: Parallax measurement is optimized when the target can be observed so that the sun-spacecraft vector is perpendicular to (+/- TBD degrees) the projection on the ecliptic plane of the sun-target vector. This spacecraft orientation occurs twice a year on opposite sides of the spacecraft's solar orbit, i.e. half a year apart.

Note 2: Being able to observe a target uninterruptedly for at least 10 minutes allows targets with V ≤ 18 to be viewed with reasonable efficiency. Shorter observation windows increase the number of visits and the corresponding overhead enough to reduce the total number of science targets

9.2 Wide-Angle Astrometry Science Requirements

Parameter	Goal	Recommend	Floor	Drivers	SRD Section
Field of regard	$\geq 20°$	$\geq 15°$	$\geq 15°$		6.1
Single observation astrometric accuracy	4 μas	8 μas	20 μas		6.1
Overall mission astrometric and parallax accuracy	2 μas	4 μas	10 μas		6.7, 6.8, 6.9, 6.12
Minimum star brightness	V=20	V=20	V=16		6.8, 6.9, 6.10
Proper motion accuracy	1 μas yr^{-1}	2 μas yr^{-1}	10 μas yr^{-1}	Note 1	6.5, 6.6, 6.10, 6.11

Note 1: The scaling between proper motion and positional accuracy is derived from observational simulations

9.3 Narrow-Angle Astrometry Science Requirements

Parameter	Goal	Recommend	Floor	Drivers	SRD Section
Field of regard	3°	1°	1°		6.10
Single observation astrometric accuracy	0.15 μas	0.5 μas	3μas		Note 1; 6.2, 6.3, 6.4, 6.10
Minimum star brightness	V=13	V=13	V=13		6.2, 6.3, 6.4
Proper motion accuracy	0.5 μas yr^{-1}	1 μas yr^{-1}	5 μas yr^{-1}		6.10

Note 1: Single observation astrometric accuracy is taken as half the semimajor axis of the astrometric wobble, that is, half the "astrometric signature" as used in §§ 6.2 and 6.3. This factor, only estimated so far, accounts for the distribution of eccentricities and inclinations in the binary systems and how the distribution of observations might interact with those variables to make derivation of the correct orbits difficult.

9.4 Rotational Synthesis Imaging Requirements

Rotational Synthesis Imaging is a science requirement

Parameter	Goal	Recommend	Floor	Drivers	SRD Section
Spectral Resolution	1000	100			7.6
Spectral Coverage	400–1200 nm	450–900 nm			
Minimum Baseline and Spacing	0.5 m	1 m			
Maximum Baseline	12 m	10 m			

9.5 Nulling-Imaging Requirements

In addition to Rotational Synthesis Imaging, Nulling-Imaging requires the following (note that this is separate from the Technology Demonstration of nulling required as the technology precursor for TPF. Those requirements are in a separate document):

Parameter	Goal	Recommend	Floor	Drivers	SRD Section
Broadband Achromatic Null	10^{-5}	10^{-4}			7.6

10 FAME

10.1 GAIA and FAME

In its Final Report (1996) the SISWG went to some length to characterize the similarities and differences between SIM and the proposed European Space Agency mission GAIA (1997). We would make few, if any, changes in that comparison. Still, the Space Astrometry landscape could hardly have changed more since that report. In early Fall 1999 NASA announced that the USNO/NRL/Lockheed Martin/CfA proposal for the Full-sky Astrometric Mapping Explorer (FAME) had been accepted as a MIDEX mission and scheduled for a 2004 launch. This marks the second event (the Phase A start for SIM being the first) in a remarkable turnaround for the US Space Astrometry effort.

The news got better. Shortly after the MIDEX announcement the Navy announced it would fund FAME's extended mission, guaranteeing a 5 year mission. With the extended mission the specifications for FAME become impressive: of order $35\,\mu$as positional accuracy at V = 9, dropping to $300\,\mu$as at V = 15. With the extended interval, proper motion accuracies should reach 25 and 250 $\mu\mathrm{as\,yr}^{-1}$, respectively. 40 million stars will be measured to V = 15, the survey being complete to about V = 14.

10.2 FAME's overlap with SIM

The impact on SIM is substantial. Unlike GAIA, FAME will preceed SIM. Like GAIA, FAME will be a scanning instrument covering the whole sky down to the above limiting magnitudes. With smaller apertures, the magnitude limits and mission accuracies will be substantially less than projected for GAIA (4 μas positions at V = 15). Even so, important questions identified in the Science Requirements section will be effectively answered by FAME, in some cases even better than SIM could. In turn, FAME's contributions to constructing SIM's input catalog should dramatically improve the latter's scientific effectiveness.

An example of the former would be FAME's ability to calibrate the luminosities of luminous stellar objects (cf. §6.6). This will be done to sufficient accuracy by FAME and many more members of the various types will be observed than could ever have been considered for SIM. The Cepheids deserve special mention in this context. To test and confirm our understanding of the pulsation process requires accurate distances to Cepheid members of open clusters where reddening, age and metallicity can be independently estimated. There are of order 25 such objects accessible to FAME, which will provide a robust basis for comparison. SIM's contribution here will be at best incremental.

More complex is the calibration of the period-luminosity relation. The objects used in distant galaxies are those at the bright end of the relation with periods typically well in excess of 20 days. FAME has access to only three such objects with distance measurements accurate to 10%. SIM will improve those distances but will add direct distances to only 2 others. Neither of these efforts will be sufficient to provide the secure calibration these fundamental standard candles require. The calibration of the Cepheid P–L relation at the bright end requires the determination of accurate distances to external galaxies, such as provided by SIM's measurement of Rotational Parallaxes.

Another area highlighted in the SRD that FAME will impact is the low mass end of the mass-luminosity relation. FAME will provide 0.3% distances to binary systems out to 10 pc at V = 15 and out to 100 pc at V = 9. This will dramatically improve our understanding of the main sequence well into the M spectral class. SIM's capabilities will be required to reach the substellar boundary, however.

10.3 The Synergy

That FAME will launch before SIM will be a major plus since SIM does pointed science and depends on knowing *a priori* which objects it needs to observe. This is particularly true in the areas of Galactic structure, for example, where identification of members of kinematic groups (*i.e.* tidal tails) are critical to the subsequent use of these groups to determine the history of the systems and the global properties of the Galaxy. FAME will make a nearly complete kinematic survey of the Galaxy within a kiloparsec and will identify likely members of kinematic subgroups to 10 kpc.

Beyond this, FAME will provide a level of serendipity lacking in SIM. In its survey mode, FAME is expected to identify numerous objects with sufficiently accurate distances and motions to know they are unusual, ideal for high accuracy followup by SIM. Even if these discoveries come late in FAME's mission the additional time interval and accuracy of a single SIM observation would provide an immediate improvement in astrometric accuracies, allowing any unusual characteristics to be confirmed even if the entire 5-year SIM measurement baseline is not brought to bear.

Best of course, would be a FAME mission completed before commencing SIM. There are numerous reasons why this will not happen. Even without that, the combination of FAME and SIM will be formidable.

11 Concluding Remarks

11.1 What We've Accomplished

In these pages we have outlined some, probably most, of the major scientific projects that will be undertaken by the Space Interferometry Mission. It is fair to say that when the mission is complete the results will become one of the great legacies of the Space Program. Distances, the most fundamental thing you can know about an astronomical object, will be measured to levels unimaginable two decades ago. We will determine the masses of the Jupiter type objects already found orbiting nearby solar type stars, extend the search for those objects to many times the number of stars and push the sensitivity to the point of detecting Earth mass companions around the nearest few stars. The fundamental technique of synthesis imaging will be demonstrated in space on real, scientifically demanding problems. Critical technologies such as broadband nulling will be demonstrated in preparation for the next great step in planet discovery, Terrestrial Planet Finder.

Our goal here was twofold: to make the case for SIM in the most concrete, defensible terms and to make sure that the relationship between instrument capabilities and scientific return were laid out clearly and in detail. This is accomplished in the sections referred to as the Science Requirements Document, § 5 – § 9. Even a quick read reveals the astonishing breadth of SIM's potential impact on the field.

11.2 The Challenge

But the SRD is really just a challenge. We, the SIMSWG, can do nothing more that articulate the extraordinary return that will come from the Mission. It is not up to us to build it, to operate it or reduce the data. It is not even ours to do the projects defined here - those scientists will be picked through the AO process, the commencement of which coincides with the demise of the SIMSWG (although many from the SIMSWG will be competing for those positions).

The real work hasn't even begun. Our contribution, we hope, will be mostly to make it hard to compromise. We do appreciate that to reach the measurement accuracies we specify here is simply impossible. We hope it is not worse than that. This document is meant to be read on those days when one of those impossibilities is encountered - as motivation. To give up on even one specification would result in a major retreat on the scientific return. Copies of the SRD should be in every first aid kit in the Project.

11.3 The Future

SIM is an optical interferometer that does astrometry. Thirty years ago one would not have conceived of the juxtaposition. Optical interferometers showing up in unexpected roles will become the rule, particularly in space. It is simply too important to see (or equivalently, use) detail and simply too expensive to do so with monolithic mirrors. That SIM leads the way and we have had a hand in it is a most satisfying circumstance.

Good luck with SIM.

12 Acknowledgements

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13 References

Allen, R.J., & Böker, T. 1998, "Optical Interferometry and Aperture Synthesis in Space with the Space Interferometry Mission", in *Astronomical Interferometry*, eds. R. Reasenberg & J.B. Breckenridge, SPIE, 3350, 561

Augereau, J.C., Lagrange, A.M., Mouillet, D., & Ménard, F. 1999, A&A, 350, 51

Backman, D.E., Caroff, L.J., Sandford, S.A., & Wooden, D.H. 1998, editors, *Exozodiacal Dust Workshop, Conference Proceedi ngs* (NASA/CP-1998-10155)

Backman, D., & Paresce, F. 1993, in *Protostars & Planets III*, eds. E.H. Levy, & J. Lunine (Tucson, U. of Arizona Press), 1253

Bahcall, J. 1991, "The Decade of Discovery in Astronomy and Astrophysics", National Academy Press (Washington, DC)

Blitz, L. & Spergel, D.N. 1991, ApJ, 379, 631

Boden, A., Shao, M., & Van Buren, D. 1998, ApJ, 502, 538

Böker, T. 1998, Report to the 4th SIMSWG meeting

Böker, T., & Allen, R.J. 1998, "Searching for Zodiacal Disks with SIM", in *Astronomical Interferometry*, ed. R. Reasenberg & J.B. Breckenridge, SPIE, 3350, 58

Böker, T., & Allen, R.J., 1999, "Imaging and Nulling with the Space Interferometry Mission", ApJS, 125 (in press)

Böker, T., Allen, R.J., & Rajagopal, J. 1999, "Measuring Stellar Proper Motions in the Nucleus of M31 with SIM - Zooming in on the Black Hole", in *Working on the Fringe*, eds. S. Unwin, & R. Stachnik (Dana Point Conference, NASA)

Burrows, C., & Krist, J. 1996,

Chaboyer, B., Demarque, P. & Sarajedini, A. 1996, ApJ, 459, 558

Dauphole, B., Geffert, M., Colin, J., Ducourant, C., Odenkirchen, M. & Harris, W. E. 1996, AJ 112, 1487

Dermott, S.F., Grogan, K., Holmes, E.K., & Wyatt, M.C. 1998, in *Exozodiacal Dust Workshop*, ed. D.E. Backman, L.J. Caroff, S.A. Sandford, & D.H. Wooden (NASA/CP-1998-10155), 59

Dominik, C., and the HJVEGA Consortium, 1998, Astrophys. Space Sci. 255, 103

Eggen, O.J., Lynden-Bell, D., & Sandage, A.R. 1962, ApJ, 136, 748

Evans, I.N., Tsvetanov, Z., Kriss, G.A., Ford, H.C., Caganoff, S., & Koratkar, A.P. 1993, ApJ, 417, 82

Faber, S.M., Tremaine, S., Ajhar, E.A., Byun, Y.-I., Dressler, A., Gebhardt, K., Grillmair, C., Kormendy, J., Lauer, T., and Richstone, D. 1997, AJ, 114, 1771

Ferrarese L., Ford H.C., Jaffe, W. 1996, ApJ, 470, 444

Ford, H.C. et al. 1994, ApJ, 435, L27

Freedman, W.L. et al. 1994, ApJ, 427, 628

Gaidos, E.J. 1999, ApJ, 510, L131

Gallimore, J.F., Baum, S.A., & O'Dea, C.P. 1996, ApJ, 464, 198

Gallimore, J.F., Baum, S.A., & O'Dea, C.P. 1997, Nature, 388, 852

Gershman, R., Rayman, M.D., & Shao, M. 1991, *IAF, 42nd International Astronautical Congress*, (Montreal, Canada, Oct. 5-11, 1991), paper no. IAF-91-421

Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425

Golimowski, D.A., Durrance, S.T., & Clampin, M. 1993, ApJ, 411, L41

Harris, W.E. 1996, AJ, 112, 1487 *also* `http://www.physics.mcmaster.ca/Globular.html`

Høg, E., Novikov, I.D. & Polnarev, A.G. 1995, A&A, 294, 287
Hosokawa, M., Ohnishi, K., Fukushima, T., and Takeuti, M. 1993, A&Ap,278, L27

Ibata, R.A., Gilmore, G. & Irwin, M.J. 1994, Nature, 370, 194

Jayawardhana, R., Fisher, S., Hartmann, L. et al. 1998, ApJ, 503, L79

Johnston, K.V., Zhao, H., Spergel, D.N., & Hernquist, L. 1999, ApJ, 512, L109

Kahn, F., and Woltjer, L. 1959, ApJ 130, 705

Kochanek, C. 1996, ApJ, 457,228

Koerner, D., Werner, M., Ressler, M. & Backman, D. 1998, ApJ, 503, L83

Kormendy, J., & Bender, R. 1999, ApJ, 522, 772

Lagrange, A.-M., Backman, D.E., & Artymowicz, P. 1999, "Planetary Material around Main-Sequence Stars", in *Protostars & Planets IV*, eds. V. Mannings and A. Boss (Tucson: U. Arizona Press) (in press)

Lauer, T.R. et al. 1993, AJ, 106, 1436

Lauer, T.R. et al. 1996, ApJ, 471, L79

Lauer, T.R. et al. 1998, AJ, 116, 2263

Lindegren, L., Perryman, M.A.C., Bastian, U., et al. 1994, in *Proceedings of the SPIE Converence # 2200 on Space interferometry*, (Kona, HI USA, 13-18 March 1994), 2200, 2

Lissauer, J.J. 1993, ARAA, 31, 129

Mao, S. & Witt, H.J. 1998, MNRAS, 300, 1041

Mayor, M. & Queloz, D. 1995, Nature, 378, 355

Mihos, J.C., Hernquist, L. 1994, ApJ, 437, L47

Miralda-Escudé, J. 1996, ApJ, 470, L113

Mishra, R. 1985, MNRAS 212, 163

Paczyński, B. 1996, Acta Ast. 46, 291

Paczyński, B. 1998, ApJ, 494, L23

Peebles, P.J.E. 1996, in *Gravitational Dynamics*, eds. O. Lahav, E. Terlevich and R. J. Terlevich (Cambridge: Cambridge University Press), 219

Perryman, M.A.C. 1986 "HIPPARCOS – The ESA space astrometry mission: Overview and status", in *Highlights of Astronomy*, J.-P. Swings, ed. (D. Reidel, Dordrecht, 1986), vol. 7

Peterson, B.M. 1997, *An Introduction to Active Galactic Nuclei*, (Cambridge Univ. Press)

Reasenberg, R.D. & Shapiro, I.I. 1979, BAAS, 11, 554

Reid, M.J. 1993, ARAA, 31, 345

Sandage, A. & Bedke, J. 1985, AJ, 90, 2001 "SB"

Sarajedini, A., Chaboyer, B., & Demarque, P. 1997, PASP, 109, 1321

Schmidt K.-H. & Boller T. 1992, AN, 313, 189 (CDS catalog VII/161)

Seral, L. & Zinn, R. 1978, ApJ, 225, 357

Smith, B.A. & Terrile, R.J. 1984, Science, 226, 1421

Space Interferometry Science Working Group (SISWG) Final Report 1996, http://www.ess.sunysb.edu/simswg/siswg/siswg.html

Thomas, P. 1989, MNRAS 238, 1319

Totten, E.J. & Irwin, M.J. 1998, MNRAS, 294, 1

Tremaine, S. 1995, AJ, 110, 628

Tully, R.B. 1988, Nearby Galaxies Catalog, (Cambridge: Cambridge Univ. Press)

van der Marel, R.P. 1999, AJ, 117, 744

Weinberger, A.J., Becklin, E.E., Schneider,G. et al. 1999, ApJ, 525, L53

Wilson, A.S. 1997, "The Narrow-Line Regions of Seyfert and Radio Galaxies", in *Emission Lines in Active Galaxies: New Methods and Techniques*, eds. B.M. Peterson, F.-Z. Cheng, & A.S. Wilson (PASP Conference Series Vol. 113), 264

A Glossary, Abbreviations and Acronyms

A.1 Glossary of terms with specific meanings

- Absolute Parallax: Parallax measured with respect to objects which do not suffer the perspective effects, at least at that epoch. The first truly absolute parallaxes in quanity were measured by the HIPPARCOS mission.

- Astrometric Reference Grid: Also, "the Grid". A grid of stars covering the whole sky roughly uniformly, whose positions (parameterized to allow for proper motions etc.) are known to high precision. The science objectives here place implicit requirements on the grid, but do not specify it; the Reference Grid itself is not considered a Science Objective.

- Carbon Star A star, usually in the late stages of its evolution, that shows signs of enhanced amounts of carbon, enough to exceed the abundance of oxygen. You don't want to know why.

- Cepheid A type of pulsating variable star, the archtype being δ Cephei. These stars follow a pulsation "Period–Luminosity" relation. That coupled with their intrinsic high luminosity has placed them in an unusually critical position as extragalactic distance indicators.

- Closing the grid: Refers to the improvement in accuracy of the overall grid which can be achieved by combining measurements over the whose sky.

- Crowded-field mode: Observation of target for which more than one additional target also produces fringes (e.g. cores of globular clusters). Requires simultaneous solution for multiple target positions; multiple (u, v) plane samples are needed.

- Field of Regard (FOR): The region of sky accessible by the science interferometer during a single quasi-inertial pointing of the spacecraft. Alternatively, the half-angle of the cone emanating from the collector along the nominal look direction where stars within the cone are observable without slewing the spacecraft (SSRD definition).

- Floor: A series of instrument capabilities and mission duration specifications which are viewed as the minimum acceptable for SIM. If a single item in the Floor specification is breached, the mission should be viewed as in jeopardy.

- Global Astrometry: Process of making accurate position measurements over angles that are a significant fraction of a radian or more. In the case of SIM, this is acheived by tying together many overlapping fields of nominally 15° diameter. See also "wide-angle" astrometry. Global astrometry requires knowledge of the whole-sky astrometric grid.

- Goal: The set of specifications that appear to be within reach of the instrument and which would produce sufficient science to be cost effective. These should be implemented as funds are available.

- Image Dynamic Range: The peak brightness of the brightest star in the final image, divided by the brightness of the largest spurious feature. Note: definitions of dynamic range in the literature vary widely.

- Local reference grid: A set of stars selected to form a reference frame for observations of one or more science targets for narrow-angle astrometry. These stars form a reference frame of higher relative precision than the astrometric reference grid; their astrometric parameters are measured relative to the astrometric reference grid where necessary, but at relatively lower percision.

- Mission accuracy: Accuracy obtained using data collected during the entire mission. Implicitly includes all refinements to the global astrometric grid and the time-dependent instrument model as well as the errors contributed by the measurement of the objects, themselves.

- Narrow-Angle Astrometry: Measurement of positions between objects separated by a small fraction of the Field of Regard. Nominally, separations of less than or approximately 1° are expected to meet the "narrow-angle" definition.

- Nulling Depth: Ratio of the intensity of the fringe on the detector in nulling mode, to the intensity of the same signal in direct mode.

- Nulling-Imaging: The reconstruction of an image after sampling over various orientations and baselines, much like synthesis imaging, only in this case with a half wave offset in the delay of one side and with the center of the null set at zero delay for each measurement. The latter causes phase information to be lost. Gained is the (substantial) reduction in intensity of any point-like source that has been placed on-axis.

- Optical band: The optical bandwidth is roughly defined to be 0.4 - 1.0 μm

- Parallax: The perspective annual elliptical motion of a star, due to the Earth's orbital motion around the Sun. Semi-major axis of ellipse is inversely proportional to distance to star.

- Proper motion: The angular velocity of an object. Typical units are $\mu\mathrm{as\,yr}^{-1}$, if velocities are in $\mathrm{km\,s}^{-1}$, distances in pc and time is in years, the conversion factor, historically called the "modulus" is $\kappa = 4.741$ AU/yr per $\mathrm{km\,s}^{-1}$. Requirements on proper motion assume a separate requirement on the time interval over which the measurement must be made. In this document, unless otherwise stated the time interval is 5 years.

- Recommendations: The set of specifications, one step above the Floor, which the SIMSWG recommends as the the "design-to" specifications. These are what should be within the instrument's capabilities and which the instrument should be designed to achieve.

- RR Lyrae: A type of short period (¡ 1 day) pulsating variable. Often used as a standard candle to estimate distances.

- Single measurement accuracy: A 1-dimensional single observation with continuous signal integration (or series of short integrations) during which the (astronomical) signal does not change, but instrument parameters may vary. Equal to delay error, including errors from uncertainty in the four basic parameters of the science baseline orientation, divided by the projected baseline.

- Sky Coverage: The fraction of the sky that can be viewed by the system at any one time of year.

- Synthesis Imaging: The process whereby an interferometer obtains measurements of the (complex) visibility function over a range of orientations and collector separations which allows the recovery of the intensity distribution as seen on the sky, the image, over some angular range.

- Tile: A set of astrometric observations which are performed while the SIM spacecraft is inertially pointed. A tile is the second-lowest unit of astronomical data for SIM, the lowest being a delay measurement of a single science star. Loosely, a "tile" is all the observations within a given radius of the center of the optics FOR, nominally 7.5°.

- Wide-Angle Astrometry: For the purpose of specifying SIM science topics, wide-angle is defined to be the measurement of the angle between targets that are separated by a significant fraction of a circle $> 15°$ in diameter. This latter angle is equal to the anticipated SIM Field of Regard (FOR).

A.2 Abbreviations and Acronyms

ACS	Acvanced Camera for Surveys
AGN	Active Galactic Nucleus
AIM	Astrometric Interferometry Mission
AU	Astronomical Unit, $\approx 1.496 \times 10^8$ km
A_V	Total absorption in magnitudes in the V band
E_{B-V}	Reddening (B-V magnitude)
EGOs	ExtraGalactic Objects
ExNPS	Exploration of Neighboring Planetary Systems
FAME	Full-sky Astrometric Mapping Explorer
FOR	Field of Regard
FOV	Field of View
GAIA	Global Astrometric Interferometer for Astrophysics
GC	Globular Cluster
HR	Hertzsprung-Russel, also prefix for Bright Star Catalog numbers
HST	Hubble Space Telescope
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IPAC	Image Processing and Analysis Center
ISC	Interferometry Science Center
JPL	Jet Propulsion Laboratory
LMC	Large Magellanic Cloud
MACHO	MAssive Compact Halo Object
mas	milliarcsecond
$M_\odot$	Mass of the Sun
M/L	Magnitude/Luminocity
MS	Main Sequence
m_V	$\equiv$ V
M_V	Absolute Visual Magnitude (m_V at 10 pc)
μas	microarcsecond
NGC	New General Catalog (of galaxies)
NLR	Narrow Line Regions
OB	Stellar type for young massive main sequence stars
OSI	Orbiting Stellar Interferometer
pc	parsec, unit of distance = 206265 Astronomical Units, ≈ 3.26 ly
pm	picometer
PMS	Pre-Main Sequence
PTI	Palomar Testbed Interferometer
R_0	Sun-Galactic Center Distance

SIM	Space Interferometry Mission
SIMSWG	SIM Science Working Group
SIMTAC	SIM Technical Advisory Committee
SISWG	Space Interferometry Science Working Group
SMC	Small Magellanic Cloud
SNR	Signal to Noise Ratio
SOS	Son of SIM
SRD	Science Requirements Document
TBD	To Be Determined
TPF	Terrestrial Planet Finder
(u, v)	Conjugate variables in the Fourier plane for (x,y) of an image
V	apparent Visual Magnitude $\equiv m_V$
VLBI	Very Long Baseline Interferometry