K Giants as Astrometric Reference Stars for the Space Interferometry Mission

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ABSTRACT

Wide angle astrometry with the Space Interferometry Mission needs a set of several thousand grid stars distributed uniformly over the sky. The requirements for candidate grid stars are quite stringent: The photocenters of these stars have to be astrometrically stable to within a few microarcseconds, which makes binary stars unacceptable as grid stars. We search the most precise and comprehensive astrometric catalogs available today – the Hipparcos, Tycho-1 and Tycho-2 Catalogues – for possible grid stars, and discuss the properties of samples of K giants derived from these catalogs. Furthermore, we present results of a precise radial velocity study of a small proxy sample of Hipparcos K giants. We demonstrate that it is possible to find K giants with radial velocity variations smaller than a few tens of meters per second on timescales of several months. It is thus possible to detect stellar companions in samples of candidate grid stars by means of a radial velocity survey. We discuss the results of Monte Carlo simulations that address the consequences of the measurement accuracy of a radial velocity survey on the portion of undetected binary systems.

Keywords: Space Interferometry Mission, K giants, radial velocities, reference systems, astrometry, binaries

1. INTRODUCTION

The Space Interferometry Mission (SIM)[1], which is part of NASA's Origins Program and scheduled for launch in 2006, is designed to perform extremely precise global and narrow-angle astrometry. The instrument is an optical Michelson interferometer with a 10 m baseline, which allows for astrometry at the 4 μas level in wide-angle (global) mode and at the 1 μas level in narrow-angle mode (within a $\sim 1°$ field). The basic observational quantities are time delays, which can be converted to 1-dimensional projected separations on the sky when the baseline is known. In order to solve for the baseline orientation, a minimum of four reference or grid stars has to be observed along with each science target. To allow for some redundancy and attrition among the grid stars (due to problems unknown at time of launch but detected later in the mission), it is necessary to start with a larger number of grid stars. The current design schedules twelve grid stars per field-of-regard (so-called tiles), which could be either 15 or 20 degrees diameter. This results in a total of 3000 or 1500 grid stars, respectively, distributed uniformly over the sky.

The grid star concept is also essential for the construction of an all-sky catalog of absolute astrometric parameters for the observed stars. In addition, the inclusion of a small number of quasars in the SIM grid can help to reduce spurious rotation in the SIM reference frame. In turn, radio-loud quasars can provide a link between the optical SIM reference system and the radio-based International Celestial Reference Frame (ICRF) and the corresponding International Celestial Reference System (ICRS), which can lead to improvements in these latter systems[2,3].

The final astrometric accuracy achievable with SIM strongly depends on the astrometric stability of the grid objects. They have to fulfill a number of requirements, which makes finding suitable grid stars a rather difficult task. In order to keep observing times short during each of the about 110 visits per grid star, the apparent magnitude of grid stars should in general not be fainter than about 12 mag. We already mentioned that they have to be distributed uniformly over the sky, which precludes using only O and B stars as grid objects.

The most stringent criterion however is the astrometric stability of the photocenter to within a few microarcseconds, which is almost three orders of magnitude smaller than the accuracy that was achieved with Hipparcos, the

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most accurate astrometric mission to date. Double stars are completely unacceptable as grid stars, since the astrometric jitter, the residual non-modeled uncertainty in the positions of the photocenter, would be much larger than a few microarcseconds. Even planets can impose problems, but the astrometric signature of those can be minimized by placing the grid objects at the maximum possible distance. Since there is a limit on the apparent magnitude of grid stars, this calls for intrinsically bright objects like K giants. M giants would be even better suited in terms of intrinsic brightness, but most of them are strongly variable, which would impose additional problems.

A typical 12 mag disk K giant would be located at about 2 kpc, a metal-weak halo K giant of the same apparent magnitude up about 5 kpc. At these distances, the astrometric signature of a Jupiter-like companion would be 2–5 μas peak to peak, at the limit of what is acceptable for SIM. Since it is not possible with the instruments at hand today to assure the absence of planets for such a large sample of candidate grid stars before the launch of the mission, selecting grid stars with smaller distances would be even more problematic. Cleaning the candidate grid star sample from objects with stellar companions is already quite challenging in terms of observing resources, but absolutely necessary to ensure the astrometric quality of the grid. Brown Dwarfs seem to be very rare as companions[4]. Therefore, after ruling out stellar companions, perturbations on the motion of the primary can only be caused by planetary companions.

In the following we describe how to select candidate grid star samples from the Hipparcos and Tycho Catalogues as well as the results of a precise radial velocity study for a nearby proxy sample of Hipparcos K giants. We conclude with some remarks on a strategy for the elimination of unwanted multiple systems among a sample of candidate grid objects.

2. SELECTION OF STARS FROM THE HIPPARCOS AND TYCHO CATALOGUES

The Hipparcos and Tycho Catalogues[5] are the major outcome of the Hipparcos Space Astrometry Mission. The Hipparcos Catalogue contains about 120 000 stars brighter than 12 mag, with an astrometric accuracy of about 1 mas for positions and parallaxes and 1 mas/a for proper motions. It is the most precise astrometric catalog available today, which makes it a natural source to look for astrometrically excellent stars as required for the SIM grid. The Tycho Catalogue (now also called Tycho-1) and the only recently available Tycho-2 Catalogue[6] contain a much larger number of stars, but at a lesser astrometric accuracy.

2.1. Hipparcos Catalogue

The wealth of information available in the Hipparcos Catalogue allows for a thorough selection of the K giants in the catalog as well as (at least to some extent) the identification of binary or multiple systems or other stars that might impose problems if used as grid stars, e.g. highly variable stars. Moreover, the comparison of the instantaneous Hipparcos proper motion with the long-term TRC[7] or ACT[8] proper motions can reveal astrometric binaries.[9] As described in more detail in Frink et al.[10], the application of a number of selection criteria ensuring the K giant nature of the stars as well as a certain astrometric quality along with no indications for duplicity or variability leads to a final sample of about 12 000 K giant grid candidates.

However, so far we have not applied a criterion which selects only faint and distant K giants. In fact, the completeness limit of the Hipparcos Catalogue varies between V=7.3 and 9.0 mag, and the vast majority of stars is brighter than 10 mag. Only of the order of one hundred stars in this sample of preliminary grid candidates is actually fainter than 10 mag, with distances between 800 and 1500 pc as needed for the grid.

2.2. Tycho-1 Catalogue

Clearly, a more comprehensive catalog is needed to identify a larger number of grid star candidates with distances of at least 1 kpc. Therefore we searched the Tycho-1 Catalogue, which contains about 1 million stars down to about 11.5 mag, with a completeness limit around 10.5 mag. But since there is virtually no parallax information available for the Tycho-1 stars (the errors on the quoted parallaxes are so large that the parallax values are practically useless), we had to find some other way of identifying late-type giants among the sample. We considered only stars with $B-V>1$ mag, which preserves all the K giants, but already sorts out some of the K dwarfs (K giants are about 0.2 mag redder than K dwarfs of the same spectral type). We calculated very rough photometric distances for these stars by assuming either a giant (luminosity class III) or a dwarf (luminosity class V) absolute magnitude typical for the respective color. We then took the proper motion from the TRC catalog and calculated the space velocities which would result from either of the two very different distances.

Table 1. The criteria which were applied to the sample of Tycho-1 stars to ensure the astrometric and photometric quality as well as the absence of stellar companions to the extent possible with the catalog data. Following a running number in the first column the second column specifies the field name of the parameter in the Tycho-1 Catalogue. The third column provides a short explanation of the parameter or flag, and the last column finally shows our requirements (⊔ means that this flag is not set for the star).

astrometry			
1	T10	[reference flag for astrometry]	⊔
2	T30	[goodness-of-fit parameter, $F2$]	≤ 3
3	T40	[astrometric quality flag, Q]	≤ 5
4	T41	[signal-to-noise ratio, F_S]	> 5
5	T42	[source of astrometric data]	H or ⊔
6	T57	[notes on dubious entries]	⊔
photometry			
7	T7	[source of V magnitude]	⊔
8	T36	[source of photometric data]	N, M or ⊔
9	T44	[estimate of V_{T} scatter]	< 1 mag
variability			
10	T47	[previously known or suspected as variable]	⊔
11	T48	[variability from Tycho]	⊔
duplicity			
12	T1	[Tycho number, TYC3]	1 only
13	T2	[proximity flag]	⊔
14	T49	[duplicity from Tycho]	Y or ⊔
15	T51	[CCDM component identifier]	⊔

For most of the stars the results spoke clearly for either a giant or a dwarf classification, simply by rejecting very extreme cases for the distances and/or velocities. Out of more than 200 000 Tycho stars with $B-V$ significantly larger than 1 mag and available proper motions, we classified about 100 000 as bona-fide giant stars. It is likely that there are still some dwarfs present in our sample of giant stars, and also that we have rejected some giants, especially with unusually high proper motions. However, the sample is sufficiently large so that a small contamination with K dwarfs (which can easily be identified spectroscopically) is not a great concern.

In the next step we eliminated stars with hints for any kind of variability, multiplicity or low astrometric quality (which could be due e.g. to unresolved multiplicity). We applied all the criteria listed in Table 1. In addition, we required each Tycho-1 star to have a proper motion determination in TRC, ACT *and* STARNET[11] (a proper motion catalog with about 4.5 million entries down to about 12.5 mag) with precisions of at least 5 mas/a in either coordinate for TRC and ACT and 8 mas/a for STARNET, respectively. Significant proper motion differences between catalogs were not allowed, i.e. had to be smaller than 10 mas/a between TRC and ACT and smaller than 20 mas/a for the comparison with STARNET. This left us with about 35 000 stars, but only about 18 000 stars were fainter than 10 mag and could be regarded as possible candidate grid stars.

It should be noted that at first glance it looked as if the selection criteria worked as well for Tycho-1 as they did for Hipparcos (for both samples about one third of the stars passed the tests). However, nearly half of the stars from Tycho-1 have been rejected because no investigation of duplicity was carried out for them during the Tycho-1 data analysis. Taking this into account, we were able to identify twice as many potentially problematic stars in Hipparcos as in Tycho-1, with the result that the Hipparcos sample is much cleaner than the sample drawn from Tycho-1.

Table 2. The criteria which were applied to the sample of Tycho-2 stars to select only those stars best suited as astrometric grid stars. Compared to Hipparcos or Tycho-1, much less information is available for the stars in Tycho-2.

astrometry			
1	g_mRA	[goodness of fit for mean RA]	≤ 2
2	g_mDE	[goodness of fit for mean Dec]	≤ 2
3	g_pmRA	[goodness of fit for pmRA]	≤ 2
4	g_pmDE	[goodness of fit for pmDE]	≤ 2
photometry			
5	$\sqrt{e\_BT^2 + e\_VT^2}$	[combined standard error in B_T-V_T]	$\leq 0.3\,\mathrm{mag}$
duplicity			
6	pflag	[mean position flag]	$\sqcup$
7	prox	[proximity indicator]	999
8	posflg	[type of Tycho-2 solution]	$\sqcup$

2.3. Tycho-2 Catalogue

Recently, the Tycho-2 Catalogue has become available. It is based on exactly the same observational material as the Tycho-1 Catalogue, but a more detailed reduction of the data has been carried out. This resulted in a catalog with about 2.5 million stars up to 12 mag, and, in connection with ground-based catalogs, to proper motions for most of the stars with an average accuracy of 2.5 mas/a. Photometry in the Tycho B_T and V_T bands is also available.

The first step to identify a K giant sample from the Tycho-2 Catalogue involved the conversion of the Tycho B_T and V_T magnitudes to the Johnson B and V system. The conversion depends on the spectral type and luminosity class[12], so for every potential K star two slightly different Johnson B and V colors have been computed. Only stars with a $B - V$ color index between 1 mag and 1.6 mag, derived assuming luminosity class III, have been kept for further investigation. Photometric distances and space velocities have then been computed in the same way as for the Tycho-1 sample, and about 100 000 stars in this sample with distances larger than 1.5 kpc have been identified as possible K giants (only stars which are not already in the Hipparcos or Tycho-1 catalogs are considered here). K giants with indications of potential problems regarding their use as astrometric reference stars have been eliminated with the help of the criteria listed in Table 2. Note that no systematic investigation of duplicity has been carried out during the Tycho-2 data reduction and no variability information is available for stars found only in Tycho-2. On the other hand, stars with larger photometric errors also had to be rejected, because otherwise one can not reliably establish the K giant nature. Finally, about 8000 bona-fide K giants with computed distances larger than 1.5 kpc were kept as possible grid star candidates.

2.4. Comparison of the Samples and Alternatives

The distance distribution of all three candidate grid star samples is shown in Fig. 1. As discussed earlier, it is highly desirable that the grid stars are located at the largest possible distances in order to keep the astrometric jitter at a minimum, favoring the Tycho-2 sample. However, the fraction of so far undetected multiple stars is expected to be largest for this sample, since much less information is available for stars listed only in Tycho-2 as compared to Hipparcos or Tycho-1 stars. The faintest stars in the Hipparcos sample might be very good candidates, too, but there is only a very small number of them. The Tycho-1 sample is intermediate between the Hipparcos and Tycho-2 samples in terms of distances and binary contamination.

It should be noted that a completely different strategy to select faint K giants as candidate grid stars is followed by Majewski et al.[13]. They are currently conducting a photometric and spectroscopic survey of small patches distributed evenly over the whole sky, with the intention to identify metal-weak K giants of about 12 mag suitable for the SIM grid. There might be some overlap with the Tycho-2 sample discussed here, although our selection criteria favor giants with disk kinematics (Halo K giants are more difficult to distinguish from K dwarfs on purely kinematic grounds).

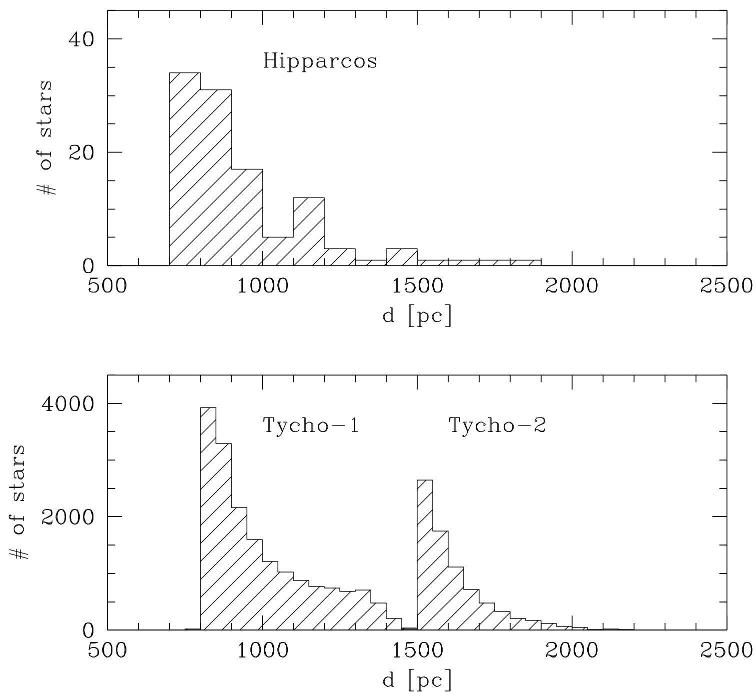

Figure 1. Distance distribution for the Hipparcos (110 stars), Tycho-1 (17 731 stars) and Tycho-2 (7747 stars) samples discussed in the text. All distances have been computed using $B-V$ colors and typical luminosity class III absolute magnitudes for disk giants. Because of the largest distances the Tycho-2 sample would probably make up the best sample of candidate grid stars, although the binary contamination might be largest in this sample.

The great advantage of the sample by Majewski et al. is the large distances of the stars, up to 5 kpc. On the other hand, virtually nothing is known about these stars except for their K giant nature, so the binary fraction might be quite high. Moreover, it is unclear how stable the photospheres of metal-weak K giants are as compared to disk giants, and how precisely radial velocities could be measured for metal-weak giants given the relative weakness of lines. These could be obstacles when trying to identify stellar companions in a radial velocity survey.

3. INTRINSIC RADIAL VELOCITY SCATTER IN DISK K GIANTS

In order to demonstrate the feasibility of a radial velocity survey to identify most of the binary stars in a candidate grid star sample we defined a proxy sample of 86 nearby Hipparcos K giants. The stars were chosen in exactly the same way as described in Sect. 2.1, except that the brightest stars ($V < 6$ mag) were selected for this sample.

We started to monitor the radial velocities in this sample with a precision of 5–7 m/s. This high accuracy is crucial to really assess the level of intrinsic radial velocity variations in our sample. The variations are mainly caused by pulsations or other photospheric or chromospheric activity, although planetary companions cannot be ruled out in some cases. A few K giants are known to display variations of the order of a few hundred m/s [14], and it is not clear whether a significant number of more stable K giants exists at all.

The observations were carried out with the 0.6 m Coudé Auxiliary Telescope (CAT) at Lick Observatory. The high resolution Hamilton Echelle Spectrograph was used in conjunction with the iodine cell, which has been proven to yield very accurate radial velocities[15].

So far we have been able to get at least three observations for 56 stars over timescales of a few months. 40 stars or 71% of those show radial velocity dispersions smaller than 50 m/s. The distribution of the observed velocity dispersions is plotted in Fig. 2 and can be fitted by a Gaussian with a mean of 20.1 m/s and a standard deviation of 10.9 m/s.

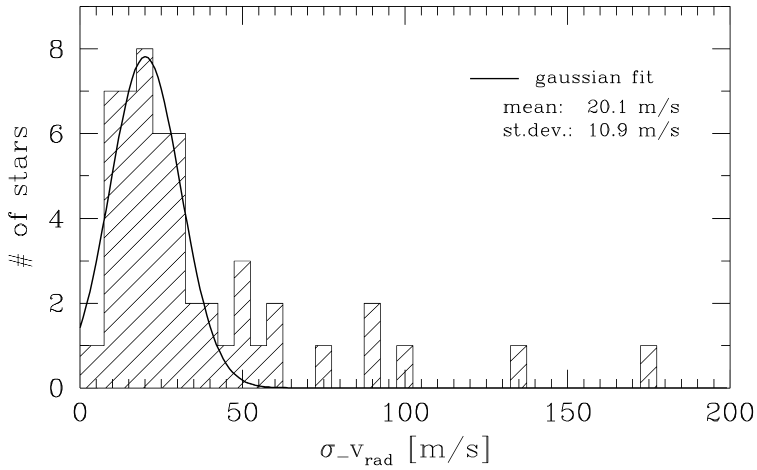

Figure 2. Observed radial velocity dispersions for our proxy sample of nearby Hipparcos K giants (hatched histogram). 4 stars with dispersions larger than 200 m/s are not shown. A Gaussian fit to the data (solid line) reveals a maximum at around 20 m/s.

This result is quite remarkable as it demonstrates that indeed some K giants show radial velocity dispersions considerably smaller than a few hundred m/s over short timescales. However, caution must be used when interpreting these results statistically. There is a strong bias in this sample against variable and active K giants, and for the unbiased sample the fraction of K giants with small radial velocity variations may be considerably larger. The selection criteria which we applied were rather strict and a large number of stars were rejected from the proxy sample, because in general more information is available for the brighter stars. The same level of a priori information will not be available for the fainter stars that will comprise the SIM grid. The next step is therefore observing a more complete sample of K giants (with less stringent selection criteria applied), as well as stars from the Tycho-1 and Tycho-2 samples, and looking for differences in the resulting distribution of radial velocity dispersions.

A few stars in our observed proxy sample are spectroscopic binaries, both previously known ones and new ones. This information is in general not available from the data in the Hipparcos Catalogue, and so they were included in our sample. This will happen more often for the Tycho-1 and Tycho-2 samples, too, with an increasing fraction of so far unknown spectroscopic binaries. However, these spectroscopic binaries are usually easy to identify with only two or three radial velocity observations.

In the next section, we address the issue how the identification of spectroscopic binaries can be achieved most efficiently in a radial velocity survey, making sure that the fraction of missed binary systems is as small as possible.

4. SIMULATION OF A RADIAL VELOCITY SURVEY

We have simulated a radial velocity survey of a sample of 3000 stars with a binary frequency of 50% in order to analyze the number of binaries which would escape detection for different observing scenarios. A duration of 5 years was assumed for the survey, and three observations per star were distributed randomly over this period of time. We assumed intrinsic radial velocity variations for both single and double stars with a Gaussian distribution and the parameters derived in the last section (Fig. 2).

The distribution of the binary orbit parameters were taken as described for other samples in the literature[16,17]. The logarithm of the periods was generated to follow a Gaussian distribution with the parameters derived by Duquennoy & Mayor[16] for a sample of solar-type main sequence stars ($\overline{\log P[\mathrm{days}]} = 4.8$, $\sigma_{\log P[\mathrm{days}]} = 2.3$). The eccentricity distribution $f(e)\,\mathrm{d}e = 2e\,\mathrm{d}e$ was also taken from that paper. However, for periods smaller than a circularization period of 100 days the eccentricity was set to zero, in accordance with observational results for a sample of about 200 K giants[17]. For the distribution of the secondary masses in this same sample Boffin et al.[17] did not find a significant deviation from a uniform distribution, and so the masses of the secondaries were generated randomly in

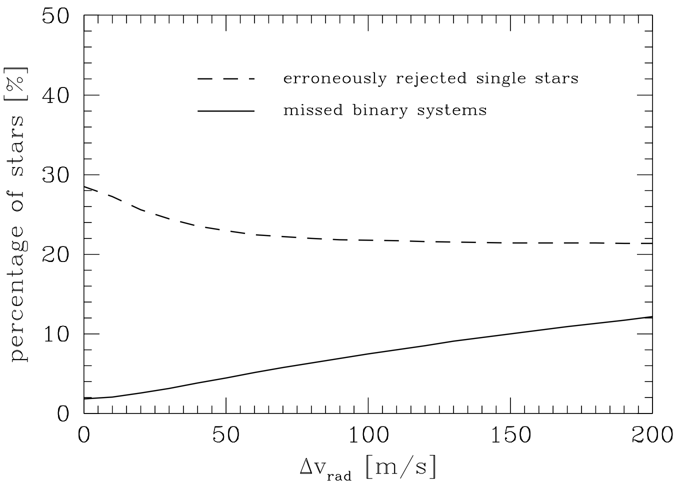

Figure 3. Fractions of missed binary systems and erroneously rejected single stars as a function of measurement accuracy in a simulated radial velocity survey with three observations per star. Distributions of orbital elements and parameters of the radial velocity survey are described in the text. The results of sets of 1000 simulations have been averaged to obtain these curves. As expected, the fraction of missed binary systems increases with lesser accuracy.

the interval between 0.1 and $1\,M_\odot$. The mass of the primary was assumed to be $1\,M_\odot$ for all systems. Random orientation of the orbits in space leads to a uniform distribution of periastron lengths and a distribution of the inclination angle i according to $f(i)\,\mathrm{d}i = \sin i\,\mathrm{d}i$. Face-on orbits with small inclinations are thus much less common than edge-on orbits, which is favorable for the detection of radial velocity signals (also scaling with $\sin i$).

A reduced χ^2 was computed from the simulated 'observed' radial velocities for each star under the assumption of constant radial velocity, given by the mean of the three observations. In order to account for the intrinsic velocity scatter, the value of 20 m/s was added in quadrature to the measurement error, and systems with a reduced χ^2 larger than 1.5 were flagged as identified binaries.

Because of measurement errors and intrinsic variability not all systems flagged this way are indeed binary systems, and for each simulation the fraction of binary systems that escaped detection as well as the fraction of single stars that were erroneously flagged as binaries is recorded.

Figure 3 shows the result of a series of simulations with varying accuracy for the radial velocity measurements, with each data point corresponding to the mean value of 1000 simulations. It is obvious that a high precision radial velocity survey can identify more binaries in the sample than one with reduced accuracy. The gain is not very large, however: even with an accuracy of 200 m/s only 12.2% of the binaries could not be identified, resulting in a 6.1% contamination of the grid sample with binaries if the binary fraction in the original sample was 50%.

On the other hand, a contamination level larger than a few percent should definitely be avoided for the SIM grid. As mentioned earlier, a minimum of four grid stars needs to be observed along with each science observation. If we assume that 5% of the grid stars cannot be used because of an unanticipated and unacceptable motion of their photocenters, and that with every science observation five grid stars are observed instead of four to get some redundancy, one can statistically expect that 9.8% of all SIM observations will be compromised because two or more bad grid stars were used. In another 34.7% of the cases exactly one bad grid star would be observed, so that one would have to get along without redundancy. In only 55.5% of the cases one would have statistically observed five good grid stars.

One can improve this situation by scheduling more grid star observations per science observation. However, this takes precious SIM observing time, and one should therefore make every effort from the ground before the launch of the mission to ensure the quality of the grid star sample to the highest possible extent. For example, if the radial velocity survey would be conducted with a precision of 20 m/s, statistically only 2.5% of the binary systems escape detection. The fraction of erroneously rejected single stars, 25.6%, would not be much larger than for a radial velocity survey with a precision of 200 m/s (21.4%). If we now assume again an additional 5% of bad grid stars and consider five grid star observations per science target, only 3.4% of the observations could not be used, and in 72.4% of the cases one would have selected five good grid stars.

5. SUMMARY AND CONCLUSIONS

We have shown that, in principle, it will be possible to select a sample of grid stars which fulfills the requirements needed for SIM, the most stringent one being the stability of the photocenter to within a few microarcseconds after correction for linear motion.

Suitable samples can be composed either by selecting K giants from existing astrometric catalogs (although with some restrictions regarding distance) or by a dedicated photometric and spectroscopic survey[13] (although with some restrictions regarding astrometric pre-selection). It would be ideal if it turns out that there is a considerable overlap between the samples selected by these two different approaches.

A dedicated radial velocity survey campaign is then needed to identify the stellar companions in a candidate grid star sample. A precise radial velocity study of a proxy sample of nearby Hipparcos K giants shows that it is possible to effectively identify stellar companions to K giants; in general, intrinsic radial velocity variations are sufficiently small not to severely affect the detection of companions, at least over timescales of a few months and for appropriately selected samples (avoiding highly variable and active stars).

We have also presented Monte Carlo simulations on the fraction of binary stars that will typically be missed in a systematic radial velocity survey, as well as on the fraction of single stars that would erroneously be rejected as grid stars. Such a radial velocity survey would consume a lot of observing resources. Obtaining tens of thousands high resolution spectra for stars as faint as 12 mag may take one hundred nights at 10 m class telescopes. But this is necessary to ensure the a priori quality of the SIM grid. Any degradation of the accuracy of measurement of the radial velocity survey leads to a higher percentage of undetected binary systems. It must be realized that this will lead to a higher fraction of unusable SIM observations.

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