TO: SIMYSO Team
FROM: CAB
SUBJECT: Reference Stars

I have started to investigate the reference star problem so that we can design our observing programs. The nominal plan for reference stars for SIM planet searches is to use K giants located as close as possible on the sky to the target stars. Distant K giants (>1 kpc) with Jupiters in 5 AU orbits will have astrometric signals at or near the SIM’s threshold. Rarer, metal poor giants are intrinsically brighter and thus for a given magnitude, are located further away with a correspondingly smaller astrometric signal from any planet. Additionally, metal poor stars may be less likely to have planets in the first place.

The SIMYSO accuracy goal is less stringent than the 1 μas needed for deep searches for terrestrial planets. Our observational requirement is to detect a Jupiter at 1 AU at 150 pc around a 0.8 M_☉ star at the 2 sigma level in each observation. Since the amplitude of the corresponding astrometric wobble is 8 μas, we want an total error of 4 μas which must be allocated between photon noise and systematic terms. The systematic error grows from 1.7 μas for stars within a 1° diameter field of view (FOV) up to 7.1 μas for stars within a 15° diameter FOV. If we use a 2° diameter FOV to contain both the reference and target stars (~1° average separation between targets and reference stars), then the systematic error will be 3 μas assuming a logarithmic interpolation between the field-dependent terms quoted above. The photon noise dependent term must be less than 2.6 μas which can be achieved on a R=12 mag star in about 1 minute. There is obviously an interplay between the reference star brightness and the target-reference star separation that can be further optimized on a field-by-field basis.

Our present understanding of the incidence of Jovian planets suggests that SIM will eventually discover that 5-10% of our reference stars have companions of a few Jupiter-mass even after spectroscopic monitoring. This means that we must enter SIM operations with 4~5 stars per field so that we can be sure to have 2-3 left. This note addresses how we will identify candidate stars, confirm their spectral type and luminosity class, and ultimately validate the absence of astrometric noise sources on a star-by-star basis.

The target stars we have identified so far are predominantly located in clusters, about 25 in total, with average field sizes of ≤1° (Table 1). To investigate the presence of suitable K giants, I undertook two catalog searches. The first utilized SIMBAD to identify known K giants (0.5 mag <B-V<1.5 mag) within a 1.5° radius (3° FOV) of the field center. SIMBAD revealed 10±1.5 candidates per field, although a few have two or fewer. While the typical brightness of these stars is V<10 mag, more than bright enough for our purposes, their number in a 2° FOV would be only ≤ 5 per field. Therefore we need to search for fainter red giants to ensure adequate coverage. I began by using Versions 2 and 3 (not yet released) of the 2MASS catalog to look for stars with the following characteristics: location within 1 degree of the field center; J<11 mag, R<12.5 mag, J-H>0.5 mag and H-K>0.1 mag; and an optical counterpart from the USNO-A catalog within 2". Typically, our fields have tens to a few hundred of these stars (“red 2MASS
The region around -76° is a complex cluster in the Chamaeleon region. Many of the purported “giants” are presumably cluster members.

To make further progress, we can take advantage of the fact that luminosity class can be determined from JHK colors for stars later than mid-K (Figure 1; Bessell and Brett 1988; Koornneef 1983). While the reddening which can be expected toward many of our clusters can scatter main sequence stars into the giant part of the color space, visible photometry can reduce these ambiguities as well as increase the spectral range over which we can make a reasonable determination of luminosity class.

To investigate the validity of using colors to separate giants and dwarfs in the relevant spectral range (K0-M0), I ran a Monte Carlo experiment in which I created dwarfs and giants using the colors mentioned above. I then “observed” these stars under 3 different scenarios: 2MASS + USNO (0.02 mag uncertainties for 2MASS; 0.2 mag for USNO B and R); and 2MASS + good R-band photometry (0.02 mag uncertainties at all wavelengths); 2MASS + good R and B band photometry (0.02 mag uncertainties at all wavelengths). I ran the calculations for 0, 1, 2, 4 mag of extinction using a $\chi^2$ value summed over all the various color combinations possible with the N bands.
In computing the $\chi^2$ value, I included $\sigma_{\text{model}} = 0.02$ mag uncertainties for the predicted colors and $\sigma_{\text{reddening}} = 0.02(A_{\lambda_1} - A_{\lambda_2})$ mag to account for uncertainties in the extinction law. A search through the (spectral type, extinction) parameter space identified the minimum $\chi^2$ solution for giants and dwarfs separately. In scoring the results, I accepted as giants stars with $\sqrt{(\chi^2/\text{dof})_{\text{giant}}} < \sqrt{(\chi^2/\text{dof})_{\text{dwarf}}} / 1.5$, $\sqrt{(\chi^2/\text{dof})_{\text{giant}}} < 2$, and spectral type accurate within 0.5 of a class. The number of degrees of freedom, $\text{dof}$, is given by the number of independent band combinations, $N(N-1)/2$, minus the number of fitted

$$\chi^2 = \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{[m(\lambda_i) - m(\lambda_j)]_{\text{obs}} - (m(\lambda_i, sp, A_v) - m(\lambda_j, sp, A_v))_{\text{model}}}{\sigma_i^2 + \sigma_j^2 + \sigma_{\text{model}}^2 + \sigma_{\text{reddening}}^2}$$

(1)

Figure 1. 2MASS JHK diagram showing the divergence between giant and dwarf stars for one SIMYSO cluster.

Figure 2. Reliability of giant-dwarf discrimination using only 2MASS data as a function of spectral type and extinction.
parameters (spectral type and, if present, extinction). Figures 2-5 give results which can be summarized as follows:

- 2MASS alone (Figure 2) does a good job (>80% reliability of identifying giants from M0 to K4 and >40% for K4-K0) in regions of no extinction, but fails if any extinction is present. Adding in USNO photometry (Figure 3) extends the range of spectral types with good discrimination up to K0 (>80% with no extinction) and improves the performance in regions of modest extinction (>40% for AV<2 mag).
- 2MASS + good R-band photometry gives excellent results over the whole spectral range for low extinction (>90% reliability), but offers only a modest improvement over USNO B&R data in the presence of extinction (Figure 4).
- 2MASS + good B and R band photometry does a good job even in regions of moderate extinction (Figure 5).

Using 2MASS + USNO data I had available for our specific SIMYSO clusters, I selected as candidate giants those stars with \( \sqrt{\chi^2/dof}_{\text{giant}} < 0.5 \ast \sqrt{\chi^2/dof}_{\text{dwarf}} \) and \( \sqrt{\chi^2/dof}_{\text{giant}} < 1.5 \). In addition, I took advantage of the absolute magnitude information to reject solutions that yielded highly reddened low mass stars that would have to be much closer than any known absorbing cloud. To accomplish this rejection, I added another term to the \( \chi^2 \) calculation, \( [(\text{distance modulus}-5 \text{ mag})/0.1]^2 \) where the distance modulus to a particular star comes from its observed magnitude and the derived spectral type and

![Giant Reliability Using 2MASS and USNO (0.2mag)](image)

Figure 3. Reliability of giant-dwarf discrimination using 2MASS + USNO data as a function of spectral type and extinction
reddening. This term was included for any dwarfs showing more than $A_V=0.25$ mag of extinction located closer than a distance modulus $=5$ mag (100 pc). Including this term makes it less likely to mistake, e.g. a true late K giant for a highly reddened early K dwarf.

This selection led to the numbers of potential giants listed for each cluster in the last column of Table 1. As illustrated in Table 2, the typical R magnitude of the 2MASS stars is 12-12.5 mag, fainter than the SIMBAD giants but still acceptable for SIM. Figure 6 shows the distribution within one cluster of target stars, SIMBAD giants, red 2MASS stars and candidate 2MASS giants.

Thus, to find our reference stars I propose we start by augmenting 2MASS-USNO data with at least one band of precision visible photometry. In some cases we may be able to use data already available from SDSS, UCAC or other surveys presently underway. In other cases we may need to obtain our own data, particularly since we need photometry for studying the potential variability of our targets. If we undertake our own photometric program, we should consider observing in narrow band filters along the lines of Majewski et al (2001) to do a still better job of pre-selecting (metal poor) giants in advance of the spectroscopic program.

Figure 4. Reliability of giant-dwarf discrimination using 2MASS + precision R band data as a function of spectral type and extinction
Once we have identified giants with ~50% reliability, we will need to determine definitively which of these candidate stars really are giants, preferably ones of low metallicity. This could be accomplished with visible photometry in intermediate band filters or through a first round of spectroscopy. To maximize the distance to these giants, we will select those with the lowest possible reddening. Once spectroscopy (at the level of 50 km/s) has certified a star as a giant, we can pursue a 2nd and 3rd epoch over the following 2-3 years to eliminate stars with companions. We will need initial spectroscopy of ~20 stars per cluster to ensure ending up with ~5 bona fide giants at the beginning of SIM observations. This observational requirement, along with the need to examine our T Tauri targets for binarity, will be well suited to multi-object spectrographs available to team members.

I have put the data for all the fields on a website (spider.ipac.caltech.edu/staff/chas/sim/simyso_refstars/*.giant) for observing planning, in particular for assessing the feasibility of multi-object spectroscopy for a ~10-20 reference stars and 5-10 target TT stars.

**References**


Majewski, S. et al. 2001, BAAS, 198,62.03

![Giant Reliability Using 2MASS and B&R (0.02mag)](image)

**Figure 5. Reliability of giant-dwarf discrimination using 2MASS plus precision B&R-band data as a function of spectral type and extinction.**
Table 2. Sample of Giant Star Candidates (M0-K0) Derived From 2MASS and USNO-A Colors

<table>
<thead>
<tr>
<th>RA</th>
<th>DEC</th>
<th>R</th>
<th>Spec Type</th>
<th>Av</th>
<th>√χ²/dof</th>
<th>Spec Type</th>
<th>Av</th>
<th>√χ²/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>246.362</td>
<td>-24.719</td>
<td>12.3</td>
<td>K2.2V</td>
<td>2.78</td>
<td>4.27</td>
<td>M0.0III</td>
<td>1.24</td>
<td>0.57</td>
</tr>
<tr>
<td>247.257</td>
<td>-25.090</td>
<td>12.4</td>
<td>K3.0V</td>
<td>3.56</td>
<td>6.88</td>
<td>K4.4III</td>
<td>2.56</td>
<td>1.10</td>
</tr>
<tr>
<td>246.971</td>
<td>-25.369</td>
<td>12.4</td>
<td>K2.6V</td>
<td>2.46</td>
<td>3.53</td>
<td>K3.4III</td>
<td>1.82</td>
<td>0.43</td>
</tr>
<tr>
<td>246.831</td>
<td>-24.695</td>
<td>11.9</td>
<td>K3.4V</td>
<td>1.68</td>
<td>3.81</td>
<td>K3.2III</td>
<td>1.34</td>
<td>1.25</td>
</tr>
<tr>
<td>247.714</td>
<td>-24.964</td>
<td>10.4</td>
<td>K3.0V</td>
<td>1.12</td>
<td>6.85</td>
<td>K3.0III</td>
<td>0.74</td>
<td>1.24</td>
</tr>
<tr>
<td>246.518</td>
<td>-24.964</td>
<td>11.8</td>
<td>K3.0V</td>
<td>1.74</td>
<td>3.86</td>
<td>K2.2III</td>
<td>1.64</td>
<td>1.03</td>
</tr>
<tr>
<td>247.855</td>
<td>-24.382</td>
<td>12.2</td>
<td>G9.0V</td>
<td>3.94</td>
<td>4.77</td>
<td>K1.8III</td>
<td>3.00</td>
<td>0.38</td>
</tr>
<tr>
<td>247.903</td>
<td>-25.449</td>
<td>12.3</td>
<td>K0.6V</td>
<td>1.54</td>
<td>1.58</td>
<td>K1.8III</td>
<td>0.92</td>
<td>0.65</td>
</tr>
<tr>
<td>246.740</td>
<td>-24.768</td>
<td>12.4</td>
<td>K2.8V</td>
<td>0.68</td>
<td>0.82</td>
<td>K1.4III</td>
<td>0.70</td>
<td>0.27</td>
</tr>
<tr>
<td>247.394</td>
<td>-25.238</td>
<td>11.9</td>
<td>K7.2V</td>
<td>1.34</td>
<td>7.00</td>
<td>K1.4III</td>
<td>2.30</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Figure 6. Targets and possible reference stars in cluster 0428+25.