FAME Grid Star Characteristics

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1 Executive Summary

Given that the FAME grid should consist of bright (V = 8.0 to 11.0), apparently single, uniformly distributed stars of 3 stars per square degree, I have found:

- A uniformly distributed list is possible – no galactic "clumping"
- Tycho-2 is sufficient to supply the stars
- There are only a few areas of densities less than 2 stars per deg^2
- There are no areas of densities less than 1.5 stars per deg^2

2 Introduction

The FAME team's current thinking is to have a select list of stars that will be utilized to determine spacecraft rotation in real-time (on-board). The data from these stars will not be binned in the cross scan direction; the full pixelized data will be downloaded. Once on the ground, the data from this select group will be utilized to reconstruct the spacecraft attitude. Although the list of stars needed for the on-board rotation rate need not be the same as that for the on-ground attitude reconstruction, our current thinking is that they will be. For this paper, the term *grid stars* will be used for this list.

The most thorough way to analyze the characteristics of the grid star list was to select the best list using currently available data. Although some details of the list may change when we get more information, the basic characteristics will remain.

For this paper the term *candidate stars* will be used for the stars with all the characteristics desired in the grid list. The term *selected stars* will be used for the subset of candidate stars actually picked for being in the grid.

3 Desired Characteristics

The desired characteristics of the FAME grid stars are bright, unsaturated, non-variable, single stars uniformly distributed across the sky to yield about one star transiting the focal plane per second. Note that this is higher than 1 star transiting any CCD by a factor of about 2, since there are multi-columns of CCD in the focal plane. The determination of on-board rotation rate requires that a grid star transits two different CCDs, therefore the final density is dependent on the final focal plane layout.

To determine the density of stars, one should compute the amount of sky being observed per unit time. Using two FOVs and 1.1 wide focal plane and a 40 minute spin rate, the amount of sky swept out per second is

$$\frac{2 \times 1.1 \times 360.0}{40 \times 60} = .33 \ \ \text{deg}^2 \text{ per second} \tag{1}$$

Since we want 1 star per second, this translates into 3 stars per deg^2, about 125,000 stars overall.

4 Input Data and Candidate List

Grid stars, for this document, must be in the magnitude range of V = 8.0 to V = 11.0. The Tycho-2 catalogue is 99% complete for stars of V = 11.0 and brighter and contains accurate astrometry, so this is a natural catalogue to base the list. (All magnitudes mentioned in this document refer to the Tycho-2 V magnitude.) Tycho-2 also contains data on multiplicity and variability, as well as a cross-reference to Hipparcos and Tycho-1 – each with their own multiplicity and variability information.

Removal of known and suspected double should be made because their presence add another layer of complication to the determination of the spacecraft attitude. The flags in Hipparcos, Tycho-1 and Tycho-2 were used in this step. Specifics causes of stars being removed are given in the following table. In addition, $\approx$ 2500 stars in Tycho-2 with no mean position given were removed. These stars were observed by the Tycho-2 experiment but no proper motion was determined. In reality, these could be included if they are in the UCAC program. Following the removal based on the Tycho and Hipparcos flags, the candidate list contains 672,555 stars.

Catalog	*Flag label, meaning*	*Removed if...*
Tycho-2	pflag; double	flag = P
Tycho-2	prox; double	flag $\leq$ 100
Tycho-2	CCDM; double	flag $\neq$ blank
Tycho-2	posflg; double	flag = D or P
HIP	VarFlag; variable	flag = 3
HIP	m_BTmag; double	flag $\neq$ blank
HIP	CombMag; double	flag $\neq$ blank
HIP	m_Hpmag; double	flag $\neq$ blank
HIP	HvarType; variable	flag = D, P, or U
HIP	CCDM; double	flag $\neq$ blank
HIP	MultFlag; double	flag $\neq$ blank
Tycho-1	Proxy; double	flag $\neq$ blank
Tycho-1	r_BTmag; double	flag = D
Tycho-1	Q; double or non-stellar	flag = 6 or 8
Tycho-1	Var; variable	flag $\neq$ blank
Tycho-1	VarFlag; variable	flag $\neq$ blank
Tycho-1	MultFlag; double	flag = D or R
Tycho-1	m_HIP; double	flag $\neq$ blank

5 Selecting a Spatially Uniform List at the Required Density

Once the list of candidate stars is made, selection of a uniformly distributed list of the appropriate density can begin. Instead of removing candidate stars not selected for the grid, data on all candidate stars remain. However, a *selection code* is used to determine which stars are selected (code = 1), which stars are unavailable for selection because of close proximity to a selected star (code = 9), and which stars have not been selected but are available for selection (code = 0). In this way, the list can be easily changed in the event that a selected star is found to be undesirable.

The process of selecting the grid stars that I utilized can be broken down into the following discrete steps:

1. Divide sky into areas that, ideally, will contain 2 grid stars
2. Select the two best grid star in each area
3. Check surrounding areas, removing selected stars that are too closely separated
4. Identify sparse areas and try to fill them with stars.

5.1 Dividing the sky

Coding is written to select the two "best" stars in any particular region. Since the FAME grid stars should number about 125,000, the sky was divided into $\approx$ 65,000 regions, each with an area of $0.8° \times 0.8°$ in right ascension and declination. All candidates were identified with a particular region number.

5.2 Selecting the two best candidates

In evaluating the candidate stars, spatial distribution is important. I have chosen, somewhat arbitrarily, some limits on how close stars can be before they are really not aiding in the spatial distribution. Currently, the FAME spacecraft rotates 540 arcsec per second. Since we have two fields-of-view, ideally we would like stars separated by about 1080 arcsecs. I have chosen a lower limit of 300 arcsec; no two stars closer than this limit are selected. These and the limits given in the following paragraphs can be easily modified.

In each of the areas, the two "best" stars are wanted, assuming that there are two in each area and they are not in close proximity to each other. For each area, all candidate stars are gathered. When no stars are in an area, obviously none can be selected. For the case when an area contains only 1 star, that one is selected for the grid.

When only two stars are found, both are picked if they are separated by more than 540 arcsec. If the separation is 540 arcsec or less, the highest priority stars is selected. Highest priority is given to Hipparcos stars, then to the brighter magnitudes. If both stars are Hipparcos stars, then both are selected and their separation is written to an output file for checking. For our list, no two stars under 300 arcsec were selected.

When more than two stars are found in a region, all Hipparcos stars are gathered. If none is found, then the brightest star is selected along with the next brightest that is at least 1080" away. If one is found, it is kept along with the next brightest that is at least 1080" away. If two are found, then they are both selected unless closer together than 540", in which case the first is selected along with the next brightest star that is at least 1080" away. If more than two Hipparcos stars are found, then the first is kept as is that last one found whose separation from the first is greater than 540". (Actually, in each of the above cases, if no star is found at a distance greater than 1080", then the allowable separation is lowered in increments of 180" until one is found). These criteria for selection of the "best" grid stars in each area are summarized in the table below.

Total Stars	*HIP stars*	*Test*	*criteria*
0	0	no test	none selected
1	0 or 1	no test	select the only one
2	0	separation	both if sep > 540" else brighter
2	1	separation	both if sep > 540" else only HIP star
2	2	none	both
> 2	0	mag + sep.	brightest and next brightest whose sep > 540"
> 2	1	mag + sep.	HIP and brightest whose sep > 540"
> 2	2	separation	Both HIP, unless sep. < 540", then 1st HIP and brightest whose sep. > 540"
> 2	> 2	separation	1st HIP and last HIP whose sep. > 540"

5.3 Removing selected stars from adjacent areas

All selected stars are then checked to ensure that no other selected star is closer than 300". This could happen when stars from adjacent areas are near the area boundaries. In cases where two or more stars are found within 300" of each other, the one with highest priority remains selected, the others have their *selection codes* changed to 9 (not available for selection because too close to a selected star).

5.4 Filling in sparse areas

There can still remain *sparse areas* – places where the stellar density is well below the desired range. For this selection of grid stars, a *sparse area* is considered a region where there are fewer than six stars in an area covering 3 deg^2. To identify the sparse areas, a region of radius 0.977°, surrounding a field center is searched for selected stars. After the region is processed, the field center is moved an increment of 0.25°. (Experience has shown that searching and filling smaller areas moved in small increments works better than larger ones in selecting a homogeneous list). If a sparse region is found, then a search for the best fill-in star is made. One does not want to select just any star available, but one that will contribute most to the spatial uniformity. To do this, the *center of the selected stars* within this region is computed. The *anti-center* – that point on the opposite side of the region center from the *center of selected stars*, is then computed. The brightest star near this *anti-center* is then selected. All flags are changed appropriately.

6 Characteristics of the selected FAME grid stars

Using the criteria and methods outlined in the previous sections, a list of 128,308 selected stars was made from the 672,555 candidate stars. Figure 1 shows the distribution of the selected stars on the sky. It shows that a uniformly distributed list of 3 stars per deg^2 can indeed be selected from stars in the $8.0 \leq V \leq 11.0$ range. Figure 2 shows remaining sparse areas. The definition of a sparse area in this case is somewhat different than found above. Plotted are all region centers where the density is less than 20 stars in an area of 10 deg^2. To find these areas, the region centers are moved in increments of 0.25°. It should be noted that of over 160,000 regions checked, only 14 have fewer than 20 stars, and none have fewer than 18. The region clearly seen in Fig. 2 is a bright nebula with few stars from which to select.

Figure 3 shows the magnitude distribution of the candidate stars (hatched) and the selected stars (solid). Note that the vertical scale is in percentage of total of each type. As stated earlier, priority has been given to Hipparcos stars first, then to brighter stars. The bright stars priority is clearly visible here since the distribution of the candidate stars does not look like the distribution of the selected stars. However, there are more stars in the faint range that we would like. Figure 4 shows the percentage of selected HIP stars as a function of total selected stars, by magnitude. Shown in Fig. 4 is that only about 25% of the faintest stars were selected because they are Hipparcos stars. The remainder have been picked simply because there are no brighter stars in their proximity.

7 Remaining work

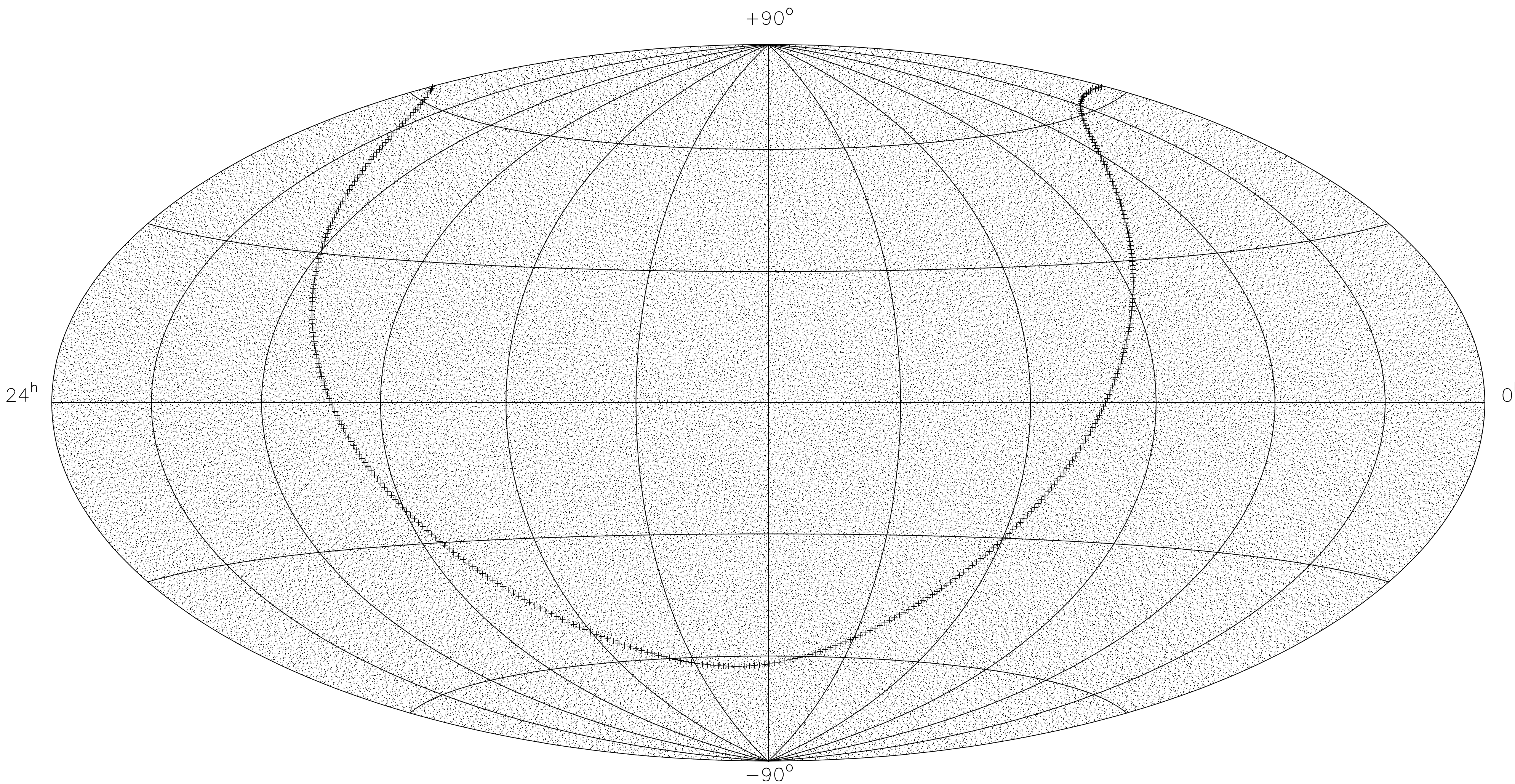
The list of grid stars selected in this study is not the final, definitive list, as the FAME team does not yet know what the characteristics of the final list should be. For example, stars in the 8.0 to 8.5 magnitude range may be over-exposed, therefore not useful for the grid. It is also possible that the one star per second distribution may need to be changed. There remains talk of changing the CCD layout in the focal plane, which may require a different density of grid stars. However, this study has indicated that for our current criteria, a well-distributed list can be made.

The next step is to put this list through the spacecraft simulator and analyze the frequency of transit rates. In this way, we can investigate regions where the transit rate fall too far below our nominal value of one per second. There remain other tasks that will need to be performed before the definitive list is selected.

Removing double based on the Washington Double Star Catalog, which over the next couple of years will incorporate both visual and spectroscopic binaries, is one obvious step. We will also identify a class of stars currently termed *astrometric binaries*. These stars have different proper motions utilizing short-period observations versus longer period ones. The type of phenomenon can be explained if the star is actually a double. Additionally, data from other programs currently underway, such as 2MASS and Tycho-3, will be utilized to further identify poor grid star candidates.

Some Science targets may also qualify as grid stars. Since these will be the highest priority targets, these may be substituted for nearby selected grid stars. It is recommended that the definitive grid star list be not selected until closer to launch, probably in the last year before lift-off.

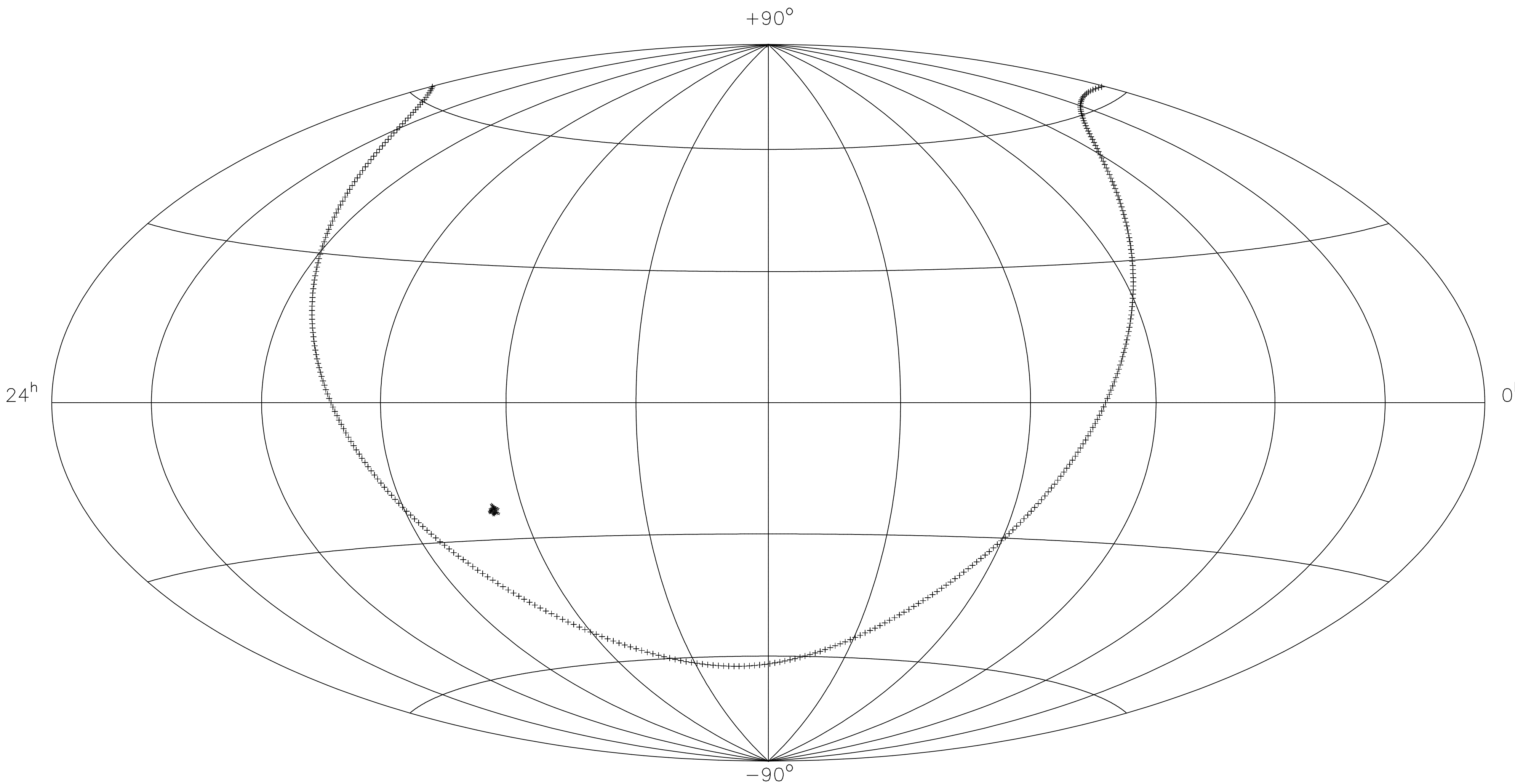
FAME grid stars



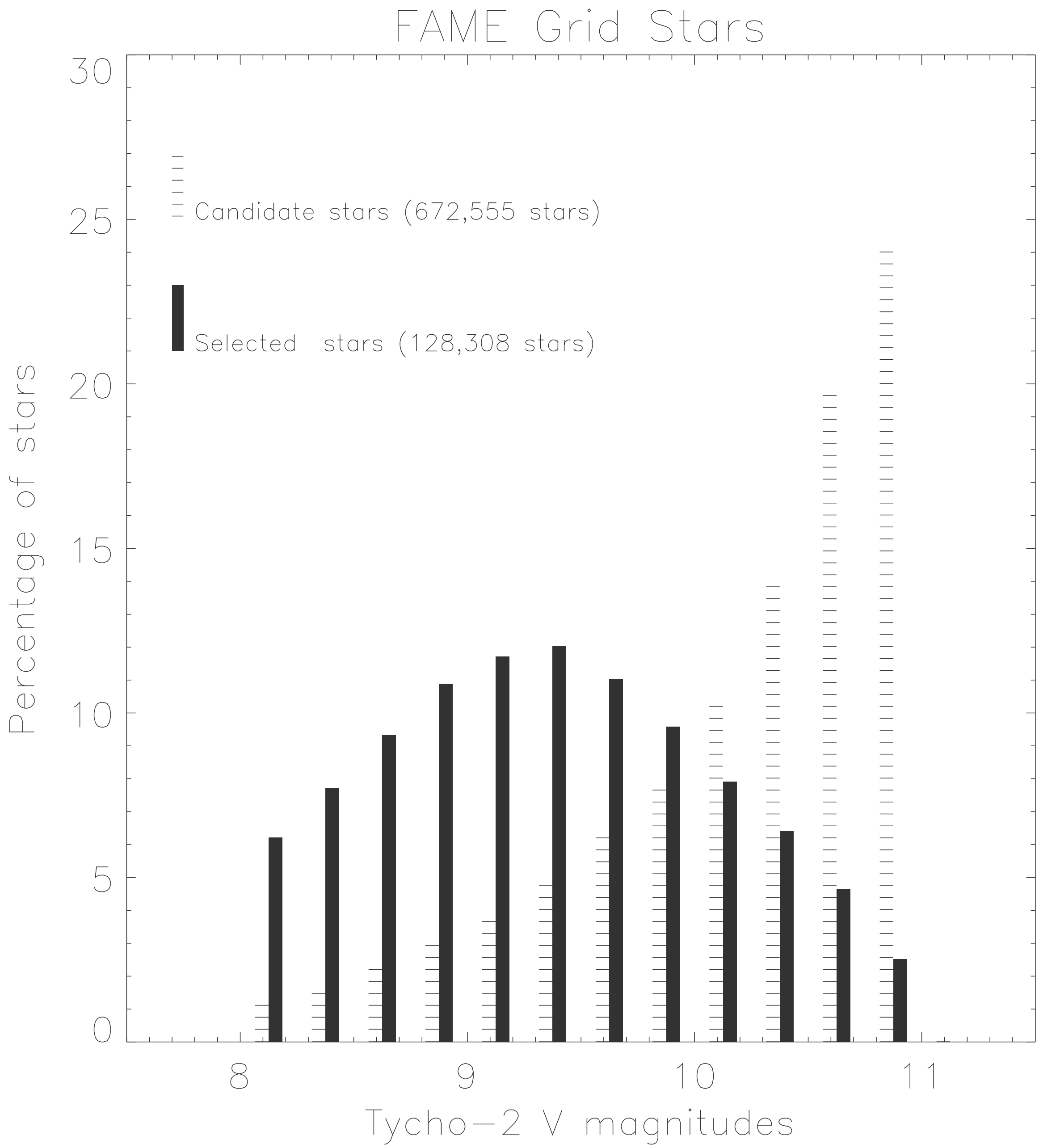
post fill−in (list.07)
Galactic Plane is shown for reference

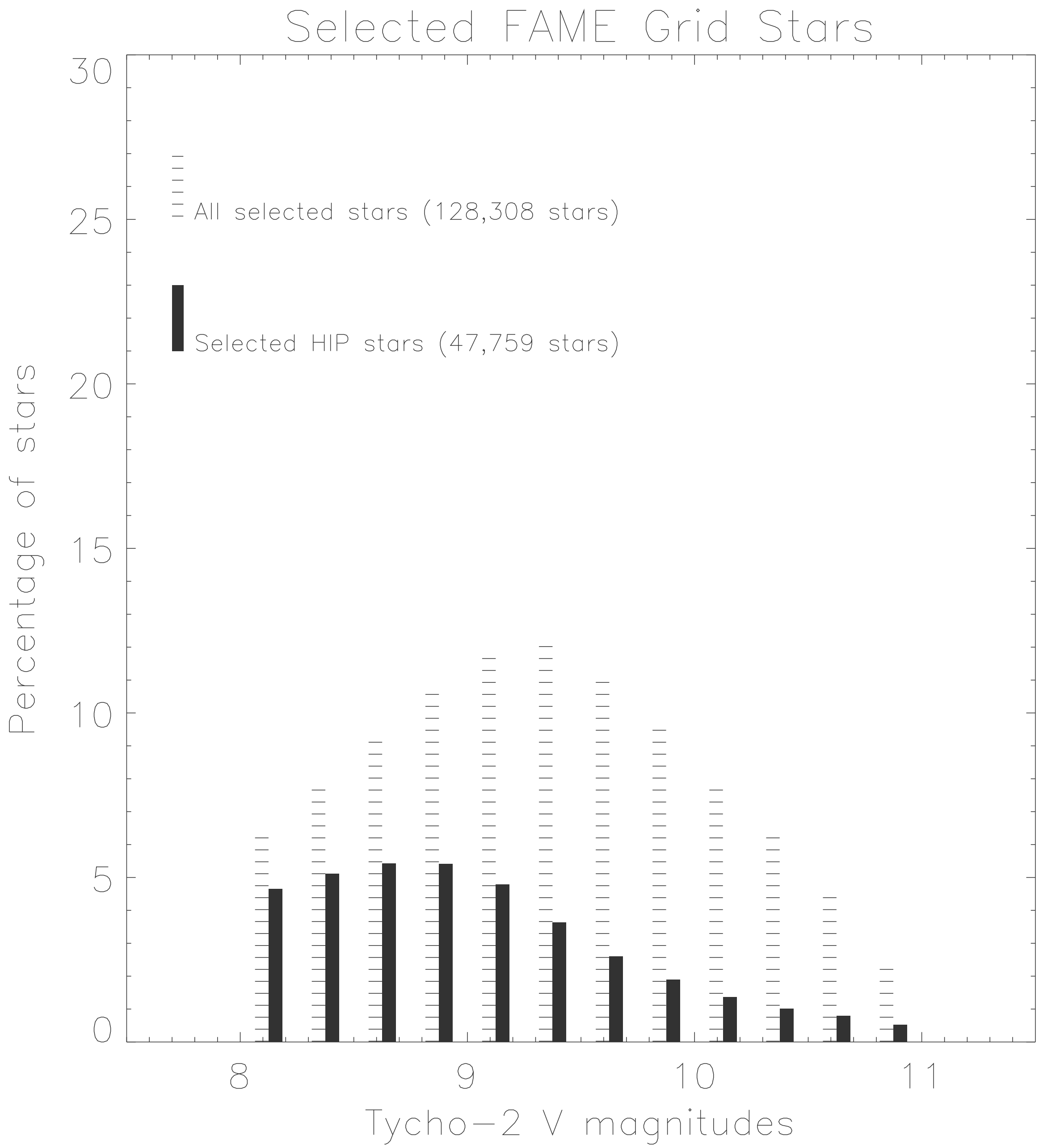
FAME Grid star sparse areas

20 or fewer stars in an area of 1.8 degree radius.



Post fill–in (list.07)
Step size = 0.25 degrees


FAME Grid Stars
Candidate stars (672,555 stars)
Selected stars (128,308 stars)
Percentage of stars
Tycho−2 V magnitudes
0
5
10
15
20
25
30
8
9
10
11


Selected FAME Grid Stars
All selected stars (128,308 stars)
Selected HIP stars (47,759 stars)
Percentage of stars
0
5
10
15
20
25
30
8
9
10
11
Tycho−2 V magnitudes