TECHNICAL REPORT

Space Telescope Science Institute
Operated for NASA by AURA

Title: Guide Star Availability for the WFIRST Auxiliary FGS using GSC2.3		Doc #: WFIRST-STScI-TR1604 Date: March 4, 2016 Rev: A
Authors: Edmund Nelan, Sherie Holfeltz, Pierre Chayer, Brian McLean	Phone: 410 338 4992	Release Date: March 30, 2016

1. Abstract

The WFIRST mission may employ an Auxiliary Guider (AG) to provide the spacecraft's attitude control system with line-of-sight measurements during wide field grism mode observations. The AG will likely be a broad band imager observing guide stars in the R to z-bands. Using capabilities previously developed for evaluating the suitability of the 2MASS point source catalog as the source of guide stars for wide field imaging observations (Nelan et al., 2015), we use GSC2.3 to determine the probability of guide star availability as a function of faint limiting magnitude of the AG. We carried out this analysis using the same three sparse fields in the 2MASS study for wide field imaging. We did not include the crowded micro-lensing survey field since slitless grism observations are not feasible in such environments. If four guide stars are needed in a single 450"x450" AG field of view, we find that the instrument needs to be able to acquire and track guide stars down to a faint limiting magnitude of $R_F = 17.5$ and $I_N = 17$ ($R_{AB} = 17.8$, $I_{AB} = 17.4$) over the sparest regions of the sky. We also compute guide star faint limiting magnitudes to be achieved if both AG channels can be used in normal operations.

2. Introduction

The Wide-Field Infrared Survey Telescope (WFIRST) mission contains a wide field imager (WFI) instrument along with a coronagraph instrument (CGI). The WFI contains eighteen 4Kx4K pixel detectors with a 0.11" pixel scale illuminated by astronomical sources through broad band filters covering a total bandpass from ~0.7μm to 2.0μm. The WFIRST pointing requirements (Spergel et al., 2015) call for the attitude control system (ACS) to stabilize the telescope line-of-sight pointing to better than 0.014" and provide absolute pointing accuracy of 0.1". This requires WFIRST to implement a fine guidance sensor (FGS) function that uses guide stars to provide the ACS with the means to determine the line-of-sight attitude knowledge. For all observing modes except the wide field spectroscopic mode (WSM), the WFI detectors execute the FGS function. However, this is not expected to be feasible for WSM observations since the grism does not provide a zero order point spread function, and it has not been determined that precise guide star tracking is possible using the higher order line spread functions. It has been proposed that WSM observations will rely on an "Auxiliary Guider", or AG (Jackson et al., 2015).

This report investigates the faint limiting magnitude this AG must achieve in order to have access to a sufficient number of guide stars for the ACS to meet its line-of-sight requirements.

3. The Auxiliary Fine Guidance Sensor

As described in Jackson et al. (2015), the AG is a two-channel instrument, each channel has a silicon-based 4096x4096 pixel detector with 110 mas/pixel, resulting in a 450" x 450" field of view. When the element wheel (EW) is in the grism position, a blue-end dichroic reflective surface illuminates the AG detectors. While both channels may be available for routine WSM observations, for redundancy, adequate pointing performance should be achievable using just one channel. It is expected that four guide stars may be needed in the operating channel to provide the ACS with sufficiently precise line-of-sight sensing in pitch-yaw. Roll is to be controlled by the star tracker assemblies (Kruk 2016 priv. communication).

The FGS function for the wide field imaging mode (WIM) observations calls for the use of pre-selected, visit specific, guide stars selected by the ground system, one per detector for up to 18 detectors. In this study we assume the same concept of guide star selection and acquisition applies to the AG, with the exception that an AG channel will have the ability (and need) to acquire *more than one guide star*. Following a slew to the target field, the AG will acquire the guide stars using 64 x 64 pixel acquisition sub arrays (7"x7"). Observations of the guide star positions will be used to update and correct the spacecraft attitude, after which each guide window (GW) will be reduced in size to a 16 x 16 pixel sub array (1.76"x1.76") for the subsequent science exposures. For WIM the GW readout is to be interleaved with the uninterrupted readout of the science data in the full frame detector, resulting in a GW update rate of ~5.86 Hz. This in turn determines the WFIRST guide star magnitude range for broad band imaging, which is anticipated to be $13 < H_{AB} < 17$ (Kruk 2015, priv. communication). It is beyond the scope of this report to estimate the expected sensitivity of the AG since the throughput, update rate, and AG bandpass is not yet specified. Instead, we compute the probability of having multiple guide stars in the AG channels as a function of guide star faint limiting magnitude. Since the AG described above will be an optical instrument, we use the optical bandpasses of the guide star catalog 2.3 (GSC2.3) as the source of AG guide stars.

4. Guide Star Catalog 2.3

GSC2.3 is the deepest all-sky catalog available. It was derived from the Digitized Sky Surveys that STScI created from the Palomar and UK Schmidt survey plates. Its original purpose was to support the operation of the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST). The original catalog contained photometry in three optical passbands; photographic J (B_J), photographic F (R_F), and photographic N (I_N). The transmission curve of each photographic passband is shown in Figure 1. The catalog reaches the depths of the photographic plates from which it was derived. This is field and plate dependent but generally $B_J < 21.5$, $R_F < 20.5$, and $I_N < 18.5$. In 2012 the 2MASS point source catalog (Skrutskie, M.F., et al. 2006) was merged into GSC2.3, the prime motivation being an enhancement for the support of the JWST mission (which observes guide stars over a bandpass from 0.6μm to 5.0μm).

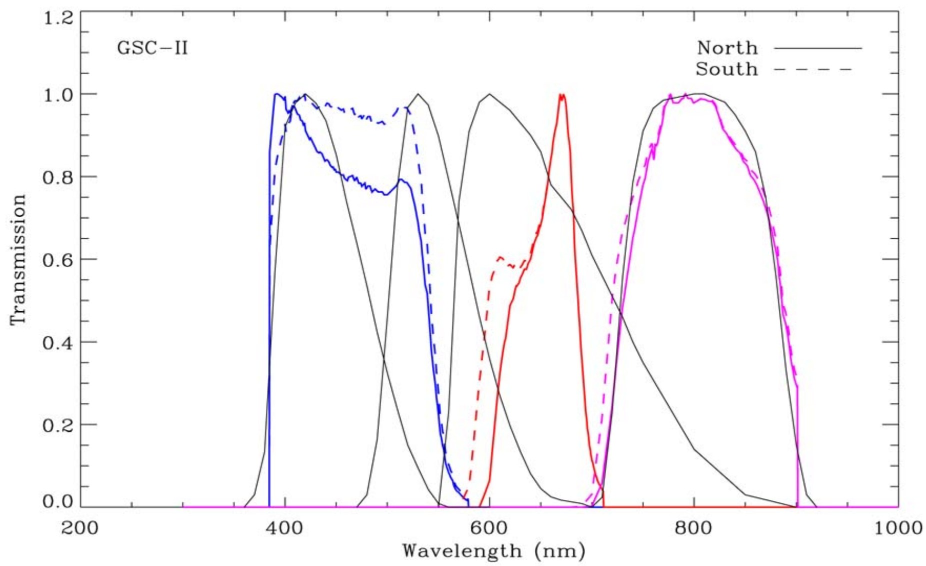

Figure 1. Transmission curves of the photographic passbands B_J, R_F, and I_N for the Palomar (solid lines) and the AAO (dashed line) Schmidt surveys, compared to the Johnson-Kron-Cousins $BVTI_C$ filters (black lines). (from Lasker et al., 2008).

For the WFIRST Auxiliary Guider, GSC2.3 is an appropriate catalog of guide stars since it can be expected that the catalog will go deeper than and be complete at the AG faint limiting magnitude. Given the expected red-end cutoff of 0.9μm and an undetermined blue-end cutoff, for the AG, both the R_F and I_N passbands are relevant to this study.

5. Evaluating Guide Star Statistics

To assess guide star availability for the WFIRST Auxiliary Guider using GSC2.3, we extracted cones of 5 degrees in radius (78.5 deg^2) from the catalog for three different pointings on the sky (Table 1). This includes a field of particular interest for the WFIRST: the High Latitude Survey (HLS) field. We also explored two other fields, the north galactic pole (NGP), and an intermediate high galactic field (HGF) at (*l,b*) = (180,-60), which similar studies by STScI (Nelan, 2004) in support of the JWST guide function were shown to be representative of the sparsest places on the sky for guide star candidates. These three fields were also explored in our study of guide star availability using the 2MASS point source catalog for WIM observations (Nelan et al., 2015). Note, that study included a field in the Micro-Lensing Survey, which we do not include here since WSM observations are not feasible in such crowded fields.

Table 1 Target fields, Celestial and Galactic Coordinates

Target Field	RA	Dec	l	b
High Galactic Latitude Survey (HLS)	314.897	-45.01	355.21	-41.02
Northern Galactic Pole (NGP)	192.859	+27.13	213.22	+90.0
Intermediate High Galactic Field (HGF)	37.99	-08.80	180.0	-60.06

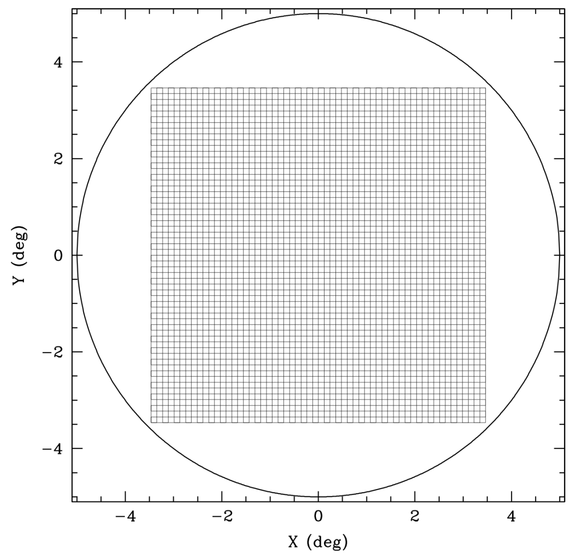

Figure 2. We used a 56x56 grid of 450"x450" detectors to sample GSC2.3 to test the assumption that the areal density of stars follows a Poison distribution. The full 5 degree radius cone was used to compute the guide star availability statistics reported below.

The catalog data of interest for this study includes, for each object: the RA, Dec, the R_F and I_N magnitudes, and its classification. For objects classified as "stars" the GSC2.3 field *class* = 0, while non-stars have *class* = 3 or 4. For a star to be a candidate guide star, it must be classified as a star, be brighter than a specified faint limit and have no neighbors (stars or non-stars) that are brighter than two magnitudes fainter than the star under consideration within a 10" distance. This isolation criteria guarantees that only the guide star (GS) will be present in the 64x64 pixel subarray (7"x7") guide star acquisition window. This isolation constraint has only modest impact for the sparse fields under consideration in this report.

After applying the brightness and isolation criteria, we place a 56 x 56 grid of "detectors" (Fig. 2), each being 450" x 450", on the field, resulting in 3136 "detectors". We compute the number of guide star candidates in each detector for a given faint limiting magnitude, and the average number of GS candidates per detector for the field. We verified that the distribution of star counts in the sample approximates a Poisson distribution (Fig. 3) over the extracted catalog. With the Poisson distribution confirmed, we apply Poisson statistics using all stars in the 78.5 deg^2 sample. This procedure was applied for faint limiting magnitudes ranging form 13 to 18 in R_F and I_N (the passbands were analyzed separately). A bright limit of 8.0 magnitudes was assumed.

The Poisson distribution, with an average number *m* of candidate guide stars per AG detector, yields the probability *Pr(k)* that *k* guide stars will be found in a given AG channel, where

$$Pr(k) = e^{-m} m^k / k!$$

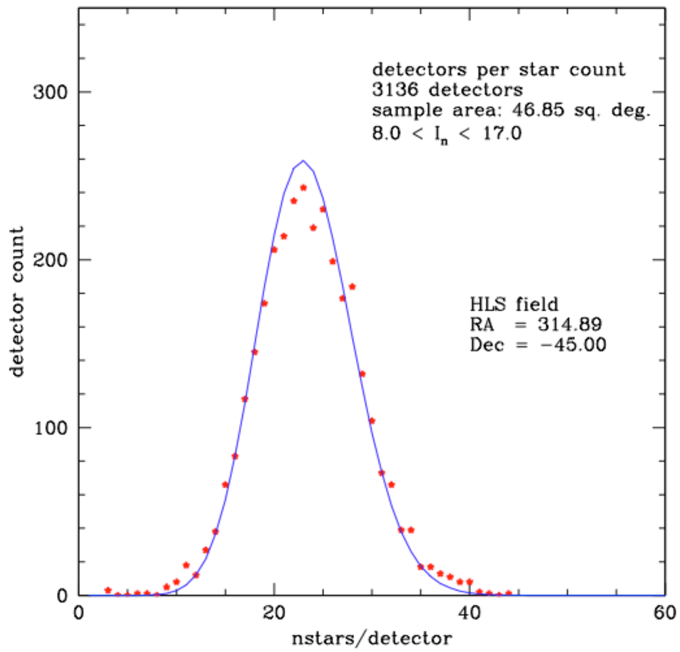

Figure 3: The distribution of star counts within the 3136 "detectors" used to analyze the HLS field (red dots) for the GSC2.3 I_N passband down to I_N = 17.0. The blue line is a Poisson distribution of the expected number of detectors containing N stars, based upon the average number of stars per detector FOV = 23.4 within the 46.85 deg^2 area covered by the grid of 3136 "detectors".

Thus, the probability that a given detector will have *at least* one guide star candidate is

$$P_1 = 1 - Pr(0).$$

Likewise, the probability that a detector will have *at least* two guide stars is given by

$$P_2 = 1 - Pr(0) - Pr(1),$$

and the probability detector will have *at least* 4 guide stars is given by

$$P_4 = 1 - Pr(0) - Pr(1) - Pr(2) - Pr(3).$$

Given that the AG may have two channels available for operations, we also compute the statistics that there will be *at least 1, 2, 3, and 4* guide stars available in the combined FOV of the two channels. In our calculations this is done by simply doubling the FOV in which to find GS candidates, which effectively doubles the value of m in the equation for $Pr(k)$ above.

6. Results

We report the candidate guide star statistics for the three selected fields using the R_F and I_N magnitudes of GSC2.3 with assumed faint limiting magnitudes ranging from 13 to 17 in both passbands for the HLS and HGF, and down to 18th magnitude for the NGP region, this study's sparest field. In all cases the 10" no-neighbor isolation criterion was applied.

Separate tests with a 15” and 20” isolation criterion were also conducted, and this was found to have no appreciable effect in these sparse fields.

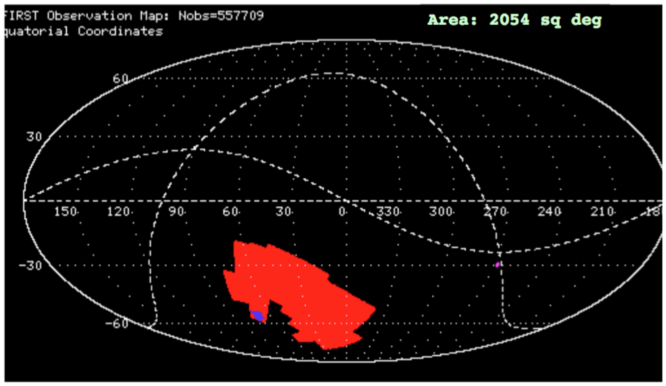

Figure 4. A representative LSST field from Hirata (2014), which is expected to be representative of the WFIRST HLS field. For this study we chose a cone of 5° radius centered on ecliptic coordinates (+45°, -45°).

6.1 High Latitude Survey

The WFIRST high latitude survey (HLS) field is expected to overlap with the fields chosen for the Large Synoptic Survey Telescope and the Euclid mission. The HLS field chosen for this study is based upon Hirata (2014), as shown in Figure 4, from which a cone of 5° radius was extracted from GSC2.3. Figure 5 shows a DSS image of an excerpt from the field overlaid with an approximate AG FOV. The R_N and I_N magnitudes of several stars are indicated to assist visualization of GS probabilities for this field.

Table 2a shows the statistics for the availability of GS candidates from GSC2.3 as a function of faint limiting magnitude in R_F. Table 2b shows the same results for the I_N passband. For each faint limiting magnitude, the following entries are shown:

m the average number of stars per AG detector

P_1 the probability that an AG detector will contain at **least one** GS candidate

P_2 the probability that an AG detector will have at **least two** GS candidates

P_3 the probability that an AG detector will have at **least three** GS candidates

P_4 the probability that an AG detector will have at **least four** GS candidates.

In the event both AG detectors are available for operation, we compute the probabilities of having at least 1, 2, 3, and 4 guide stars available in the combined FOV of the two channels.

$P2_1$ the probability that the *combined* FOVs will have at least **one** GS candidate

$P2_2$ the probability that the *combined* FOVs will have at least **two** GS candidates

$P2_3$ the probability that the *combined* FOVs will have at least **three** GS candidates

$P2_4$ the probability that the *combined* FOVs will have at least **four** GS candidates.

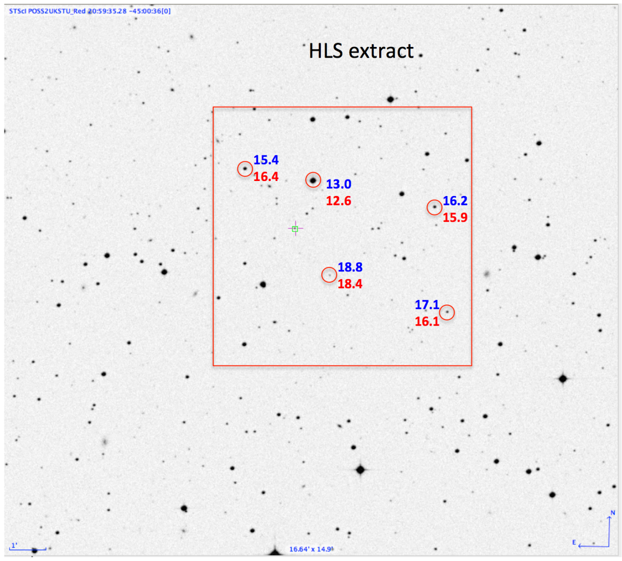

Figure 5. A digitized sky survey ~15'x15' sample from the HLS study field. The nominal AG detector FOV is shown, along with the GSC2.3 R_F (blue) and I_N (red) magnitudes for a sample of stars.

Table 2a. Guide Star statistics for the HLS field, R_F magnitudes with bright limit R_F = 8

faint limit R_F	*m*	P_1	P_2	P_3	P_4	$P2_1$	$P2_2$	$P2_3$	$P2_4$
13	1.2	0.689	0.326	0.114	0.031	0.903	0.677	0.413	0.208
14	3.2	0.957	0.823	0.611	0.387	0.998	0.987	0.950	0.874
15	6.7	0.999	0.990	0.962	0.900	1.000	1.000	1.000	0.999
16	11.9	1.000	1.000	0.999	0.997	1.000	1.000	1.000	1.000
17	18.7	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 2b. Guide Star statistics for the HLS field, I_N magnitudes with bright limit I_N = 8

faint limit I_N	*m*	P_1	P_2	P_3	P_4	$P2_1$	$P2_2$	$P2_3$	$P2_4$
13	2.1	0.866	0.597	0.326	0.145	0.982	0.910	0.767	0.570
14	4.6	0.990	0.942	0.833	0.668	1.000	1.000	0.994	0.980
15	8.8	1.000	1.000	0.993	0.976	1.000	1.000	1.000	1.000
16	15.1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
17	23.4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

6.2 Northern Galactic Pole

The region of sky near the north galactic pole is representative of sparse fields with a near minimum areal density of guide star candidates. Figure 6 illustrates an overlay of an approximate AG FOV on a DSS image of a field near the center of the study region, with the GSC2.3 R_F and I_N magnitudes labeled for several stars. Tables 3a & 3b summarize the statistics for guide star candidates in this region, using the same definitions of the columns in Tables 2a & 2b. Because of the sparseness of this field we explored GS availability down to 18th magnitude in both passbands. If four guide stars are needed with a 95% probability of availability, it will be necessary for the AG to reach faint limiting magnitudes of I_N = ~17.0 and R_F = ~17.5. If this is not feasible, then both AG fields will need to be simultaneously operable in order to meet the four GS requirement, but the AG still must achieve a sensitivity to acquire and guide on 16th magnitude guide stars.

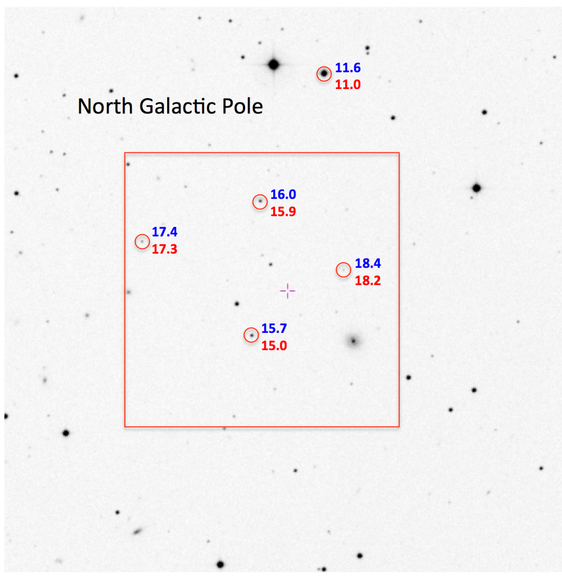

Figure 6 A digitized sky survey ~15' x 15' sample from the North Galactic Pole region. The approximate AG detector FOV is shown along with the GSC2.3 R_F (blue) and I_N (red) magnitudes for a sample of stars.

Table 3a. Guide Star statistics for the NGP field, R_F magnitudes with bright limit R_F = 8.0

R_F faint limit	*m*	P_1	P_2	P_3	P_4	$P2_1$	$P2_2$	$P2_3$	$P2_4$
13	0.5	0.378	0.083	0.013	0.001	0.613	0.246	0.071	0.016
14	1.2	0.706	0.327	0.126	0.036	0.914	0.702	0.443	0.232
15	2.4	0.909	0.690	0.428	0.220	0.991	0.952	0.856	0.704
16	4.1	0.984	0.918	0.781	0.593	1.000	0.998	0.989	0.965
17	6.6	0.999	0.989	0.959	0.893	1.000	1.000	1.000	0.999
18	10.0	1.000	0.999	0.997	0.990	1.000	1.000	1.000	1.000

Table 3b. Guide Star statistics for the NGP field, I_N magnitudes with bright limit I_N = 8.0

I_N faint limit	*m*	P_1	P_2	P_3	P_4	$P2_1$	$P2_2$	$P2_3$	$P2_4$
13	0.7	0.525	0.172	0.040	0.007	0.775	0.439	0.189	0.064
14	1.7	0.820	0.512	0.247	0.096	0.968	0.857	0.667	0.449
15	3.2	0.961	0.834	0.629	0.407	0.998	0.989	0.956	0.887
16	5.5	0.996	0.974	0.913	0.802	1.000	1.000	0.999	0.995
17	8.9	1.000	0.999	0.993	0.978	1.000	1.000	1.000	1.000
18	14.6	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

6.3 Intermediate High Galactic Latitude

We include a southern galactic field at (l,b) = (180, -60) since, in studies for the JWST mission, this was found to be similar in sparseness to the North Galactic Pole field in GSC2.3. Tables 4a & 4b summarize our findings for this field.

Table 4a. Guide Star statistics for the HGF field, R_F magnitudes with bright limit R_F = 8.0

R_F faint limit	*m*	P_1	P_2	P_3	P_4	$P2_1$	$P2_2$	$P2_3$	$P2_4$
13	0.6	0.470	0.134	0.027	0.004	0.720	0.363	0.136	0.041
14	1.5	0.786	0.456	0.202	0.071	0.954	0.813	0.595	0.371
15	2.9	0.947	0.793	0.564	0.341	0.997	0.981	0.933	0.839
16	4.9	0.992	0.955	0.864	0.716	1.000	0.999	0.997	0.987
17	7.4	0.999	0.995	0.978	0.937	1.000	1.000	1.000	1.000

Table 4b. Guide Star statistics for the HGF field, I_N magnitudes with bright limit I_N = 8.0

I_N faint limit	*m*	P_1	P_2	P_3	P_4	$P2_1$	$P2_2$	$P2_3$	$P2_4$
13	1.0	0.621	0.253	0.075	0.171	0.856	0.577	0.307	0.132
14	2.2	0.890	0.645	0.380	0.182	0.988	0.934	0.817	0.644
15	4.1	0.984	0.918	0.781	0.592	1.000	0.998	0.989	0.965
16	6.9	0.999	0.992	0.968	0.913	1.000	1.000	1.000	0.999
17	10.6	1.000	0.998	0.993	0.990	1.000	1.000	1.000	1.000

7. Conclusions

If the Auxiliary Guider is to be a two-channel instrument, with each channel having a 450"x450" FOV, and a four-guide star requirement is to be met at the 95% level using only one channel for even the sparest regions of the sky, we find that the AG sensitivity must be such that the instrument is able to acquire and track guide stars down to a faint limit of about R_F = 17.5 and I_N =17. Using the transformations from the GSC2.3 magnitudes to the AB scale (Chayer & Nelan, 2016), this implies the AG much reach R_{AB} = 17.8 & I_{AB} = 17.4. If the AG has a brighter faint limiting magnitude, then for these sparse regions both channels must be simultaneously operable to increase the area of sky so that sufficiently bright guide stars can be acquired. If fewer guide stars are needed, then the AG faint limiting magnitude can be relaxed somewhat as indicated in Tables 3 and 4. It is beyond the scope of this study to estimate the sensitivity of the AG and the number of guide stars needed for ACS performance. Once the telescope's and AG wavelength dependent throughputs, AG detector sensitivity, and guide star centroid update rate and NEA required by the ACS are known, a better assessment of predicated guide star availability can be made.

8. Acknowledgements

This work was carried out under contract with the WFIRST Study Office at NASA Goddard Space Flight Center (GSFC), as part of the joint pre-formulation science center studies by the Space Telescope Science Institute (STScI) and the Infrared Processing and Analysis Center (IPAC).

9. References

Chayer, P. and Nelan, E., 2016, *"Computing JWST FGS Count Rates using GSC2.3 and 2MASS Magnitudes"*, JWST Technical Report, in preparation

Hirata, C., 2014, "*WFIRST high latitude survey"*, Wide Field InfraRed Surveys: Science and Techniques, Pasadena, Ca,

Kruk, J., 2015, private communication

Jackson et al, 2015 "WFI Operations Concept", MCR-16_WFI Ops Concept, Dec 8-9, 2015

Lasker, B., et al., 2008, *"The Second-Generation Guide Star Catalog: Description and Properties"*, AJ 136, 735

Nelan, E., 2004, "*The Density of Stars in GSC2 at High Galactic Latitudes"*, JWST-STScI-000379

Nelan, E., et al., 2015, *"WFIRST-AFTA Guide Stars and the 2MASS Point Source Catalog",* WFIRST-STScI_TR150

Skrutskie, M.F., et al., 2006, *"The Two Micron All Sky Survey (2MASS)"*, AJ, 131, 1163

Spergel, D., et al., 2015, *Wide-Field Infrared Survey Telescope – Astrophysics Focused Telescope Assets, WFIRST-AFTA 2015 Report by the Science Definition Team and WFIRST Study Office*

10. Acronyms

ACS	attitude control system
AG	Auxiliary Guider (also AUX FGS)
EW	element wheel
FGS	fine guidance sensor
GS	guide star
GSC2.3	guide star catalog, 2.3
GSFC	Goddard Space Flight Center
GW	guide window
GRS	grism spectroscopy
HGL	high galactic latitude
HLS	High Latitude Survey
HST	Hubble Space Telescope
IPAC	Infrared Processing and Analysis Center
JWST	James Webb Space Telescope
LSF	line spread function
MLS	Micro Lensing Survey
NEA	noise equivalent angle (GS centroid standard deviation)
NGP	north galactic pole
PSF	point spread function
STScI	Space Telescope Science Institute
2MASS	two micron all sky survey
WFI	wide field imager
WFIRST	Wide Field Infrared Space Telescope
WIM	wide field imaging mode
WSM	wide field spectroscopic mode (grism spectroscopy)