EUROPEAN SOUTHERN OBSERVATORY

INTERNAL DOCUMENT

Evaluation of the catalog settings used in SADT for VISTA Public Surveys

To: VISTA IOT, SADT developer

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1 Scope of this study

The scope of this study is to find the most appropriate catalog for the selection of guide and active optics (aO) stars within the Survey Area Definition Tool (SADT), and to adopt the selection parameters (e.g. limiting magnitudes, star/galaxy classifiers) such that a smooth, non-interactive operation of the VISTA Public Surveys is ensured.

2 Motivation

One of the main problems that hampers a smooth (automatic) operation of the VISTA public surveys is the occurrence of inappropriate guide or aO stars that require an intervention of the night operator or even the abortion of the OB. The failure of a guide or aO star can have several reasons:

- The guide star is not at the expected position because it is a high proper motion star.
- The guide star is an extended source or has a too close companion that was not recognized by the selection criteria of SADT.
- The guide star is too faint, although its nominal magnitude is within the limits applied to SADT (either because the magnitude entry of the catalog is inaccurate/wrong, or the magnitude was measured in another wavelength band than I).
- The guide star is a false entry in the catalog (e.g. the photographic plates had scratches).
- Although within the defined limits, the aO star is too faint to close the active optics cycle. In this case, the night operator either increases the aO integration time or has to abort the OB (or the user has to degrade the AO priority).

So far, basically all public surveys use the GSC-2 catalog to select their guide and aO stars in SADT. The magnitude limits for guide and aO stars are based on the GSC-2 R_F band, whereas the detectors are optimized for the I-band. At the moment guide stars are selected in the magnitude range $10.0 < R_F < 16.3$ mag, and aO stars in the range $11.0 < R_F < 16.0$ mag.

Two exemplary problems that occurred during the last year of observations are:

1. The VIKING survey covers a region at RA$\sim$23h and DEC~ -31:26 which is affected by false entries in GSC-2 due to scratches on the DSS scans (see Fig. 1). The team had to redo the tiling this area with another catalog.

2. In a deep VIDEO pointing (XMM area) the aO stars of two subsequent pawprints turned out to bee too faint (15.83 and 15.72 mag) for closing the AO loop. Since the AO priority was set to HIGH the OB failed. The team had to cahnge the AO priority to NORMAL, accepting some degradation in the image quality.

Clearly, an optimization of the magnitude limits and the evaluation of other catalogs is needed to improve the VISTA operations.

3 Comparison of catalogs

The catalogs currently available in SADT are GSC-2, USNO, UCAC3 and 2MASS. So far, it was recommended to use GSC-2 for the guide/aO star search. Given the deficiencies mentioned before, another catalog might do a better job.
The hope was that UCAC3 is a much cleaner catalog than GSC-2. However, it turns out that UCAC3 is much shallower, and tests with SADT have shown that much less appropriate guide/aO stars are found. The reason for that is explained later in this report.
The use of 2MASS is hampered by the fact that the magnitude limits within SADT (or previously in the instrument package) apply to optical (R band) colours only, but the J band is used as the reference magnitude for 2MASS. Thus, even when adopting a constant offset to the magnitude limits in order to account for the average difference between R and J, stars which are severely reddened (i.e. have a very red $R-J$ colour) would be wrongly corrected, resulting in equivalent R magnitudes within the valid limits, but true R magnitudes too faint to serve as guide or aO stars.

Piskunov et al. (Astronomy Letters, 2008, Vol. 34, No. 4, pp. 256-265) developed in their paper *"Optical Extension of the 2MASS Infrared Catalog"* a procedure for transforming the 2MASS NIR magnitudes to optical magnitudes R_J, which is similar to the R band magnitude used in SADT. They also give a brief overview of the limits and deficiencies of present-day all-sky catalogs.
The conclusion of Piskunov et al. is that *'2MASS is the only deep complete catalog in which the positions and magnitudes determined in all-sky homogeneous systems whose observations are not farther than 10 years away from the current epoch'*. Also it is the catalog *'best cleaned from false objects'*.
Catalogs based on photographic observations instead suffer from *'gaps in sky regions with a high star density or with bright objects (stars or nebulae) due to the crowding effect and a large number of false objects near these gaps'*. Further citing Piskunov et al.: *'In the GSC, the completeness also depends on Galactic latitude, since the catalog in the Milky Way region was artificially sparsed. Insufficient support by deep photometric standards leads to a distortion of the magnitude scales, which is reflected in a distortion of the magnitude distribution (e.g., for the USNO catalogs).'* And regarding UCAC3: *'In the UCAC Project, Zacharias et al. (2000) virtually avoided the gaps in sky regions with bright objects by performing observations with different exposure times. However, since they eliminated all problem cases, including the stars for which the proper motions could not be determined, when compiling UCAC2, the catalog is incomplete in the entire magnitude range covered'*.

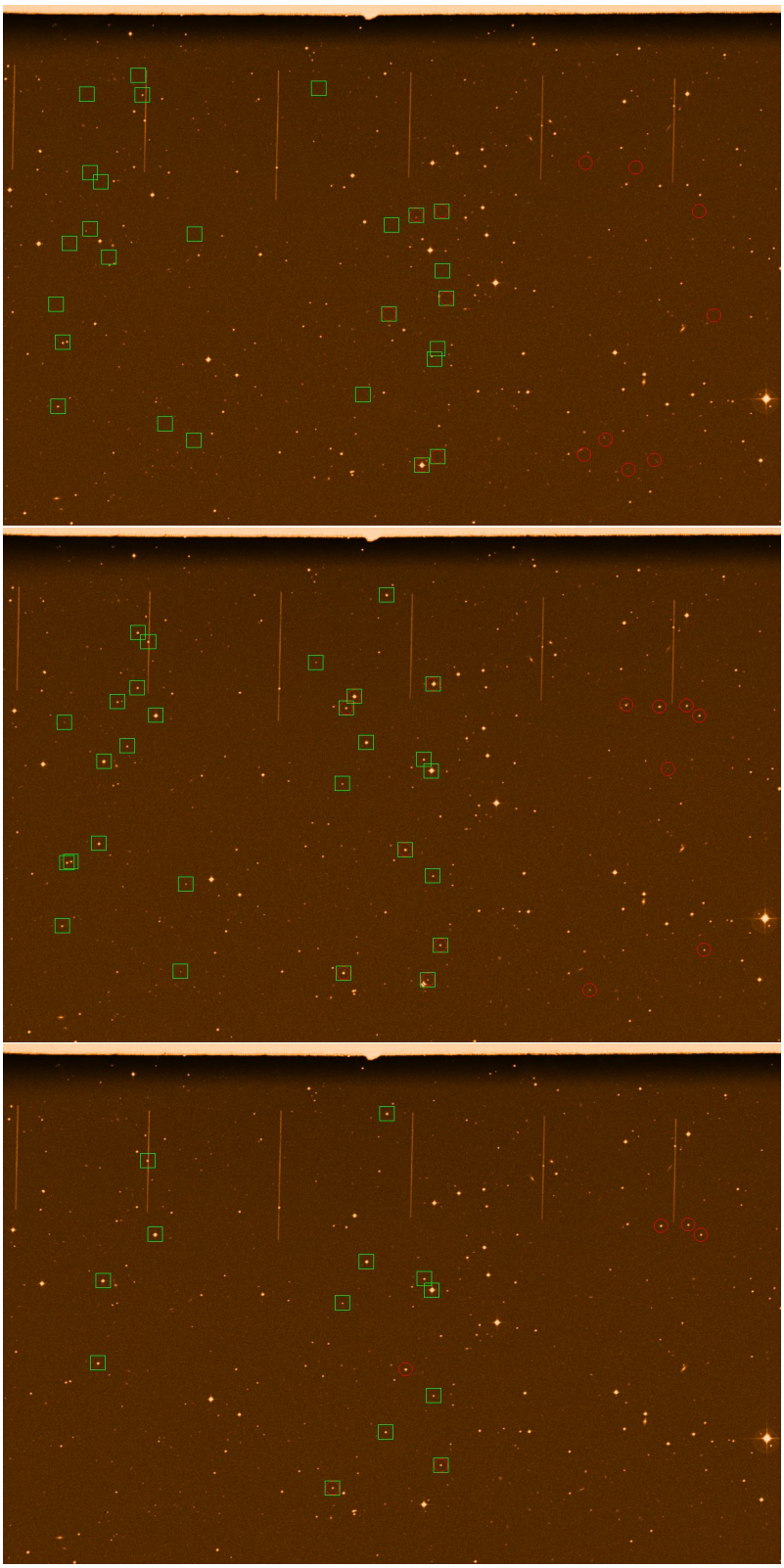

Figure 1: Selection of guide stars (red circles) and aO stars (green squares) for one VIKING OB in an area of false entries in GCS-2. From top to bottom: SADT results (from the xml file) for GSC-2, 2MASS and UCAC3, respectively. Note that many of the valid 2MASS stars are too faint in the optical because the magnitude range is based on the J band magnitude, thus very red stars will have a faint R band magnitude. The few stars found by UCAC3 are due to a non-optimized magnitude range and too strict selection criteria.

In summary, 2MASS is the most appropriate catalog for all-sky surveys. However, since most guide and active optics systems work in the optical, the NIR colours have to be transformed to an equivalent optical magnitude. Piskunov et al. provide this transformation in dependence of the Galactic latitude to correct for reddening effects. Only the J, H magnitudes and Galactic coordinates l, b have to be known for the star. Later in this report I will suggest that the Piskunov formula should be applied for the 2MASS catalog within SADT.

A side note: the JWST project published a technical memorandum on the "Algorithms for Transforming GSC-II Magnitudes into the NIR" (Doc # JWST-STScI-001410) in which formulas are given to transform B_J, R_F and I_N (all GSC-2 entries) into J, H and K_s. However, these transformations are restricted to regions of high Galactic latitude ($|b| > 30^\circ$) since they do not take reddening into account. In principle, the equations presented in this technical memorandum could be inverted and used to derive an equivalent R band magnitude from the 2MASS catalog when used in SADT.

4 Tests on a high and low Galactic latitude field

For the following tests the SADT version v5.01 was used. The new feature of this SADT version is that in the sadt.cfg file the magnitudes limits for the different catalogs can be individually adjusted and some selection parameters can be toggled on and off. Also the output on the log screen can be adjusted. For each SADT run two files were created from the log output. One that contains all the stars in the search area of the auxiliary CCDs, and another that contains only the valid stars according to the magnitude limits and or the selection flags.
Two VIRCAM tiles were defined in SADT to test the performance of all four catalogs provided in SADT: GSC-2, USNO, UCAC3 and 2MASS. One tile is located at high Galactic latitude ($b = -70^\circ$), with the centre coordinates RA=02:18:52.4 and DEC= $-$34:06:21.6. The other tile was placed at low Galactic latitude ($b = +2^\circ$), with the centre coordinates RA=17:17:02.4 and DEC= $-$34:06:21.6.

4.1 The high Galactic latitude field

Let's concentrate first on the high Galactic latitude region which should be free of reddening effects. In the following figures, I show the comparisons between GSC-2 and one of the other catalogs. One figure shows the spatial distributions of all and valid guide and aO stars in the regions of Northern and Southern auxiliary detectors. The other figure shows the difference of the reference magnitudes of both catalogs as function of the GSC-2 R_F magnitude with the limits for guide and aO star selection indicated.

Fig. 2 shows the comparison of GCS-2 with the USNO catalog. The reference magnitude of this catalog also is in the R band. One recognizes immediately that USNO is the deeper catalog. Within the valid magnitude regime the difference of both reference magnitudes is on average close to zero, although the distribution has quite a large scatter and seems to be skewed, as also noted in the Piskunov et al paper. In general, all the stars that were selected as valid guide/aO stars in GSC-2 also were selected in USNO and vice versa. Thus, both catalogs are more or less equivalent at high Galactic latitude fields.

In Fig. 3 the comparison of GCS-2 with UCAC3 is shown. The reference magnitude of UCAC3 is centred on 710 nm, different from the GCS-2 R_F band. In order to find enough guide/aO stars with UCAC3 backtracking was necessary. So the detector fields are only partially overlapping, as

can be seen in the coordinates plot. The search for UCAC3 stars was run twice, once with all quality/selection flags toggled on, and once woth all those flags toggled off. In a later section the individual quality/selection flags are explained in more detail. Although the areas of GSC-2 and UCAC3 do not overlap fully, it is clear that UCAC3 is very shallow and does not contain all the valid GSC-2 stars and that the selection criteria are too strict. Moreover, it is evident that the two reference magnitude are not the same. There exists a difference of ~ 0.7 mag, in the sense that the UCAC3 magnitude limites should be fainter by this amount, which partly explains why fewer UCAC3 stars were found by SADT.

Fig. 4 shows the comparison of GCS-2 with the 2MASS catalog. The reference magnitude of 2MASS is the J band with the same magnitude limits applied as for GCS-2. The spatial distribution of GCS-2 and 2MASS stars does not match one-to-one. There are GSC-2 stars that are nor present in 2MASS and vice versa. However, there still is a fair agreement for stars that are at the end selected as valid guide/aO stars. For stars brighter than $R < 15$ mag or bluer than $(R - J) < 1.3$ there is a rather constant offset of ~ 0.9 mag between the R_F and J magnitude. Thus, for high Galactic latitude fields a simple adjustments of the limiting magnitudes might work quite well. But note also that still some faint red stars would remain that would cause the guide/aO system to fail when selected.

4.2 The low Galactic latitude field

The study of the guide/aO stars for the tile located at low Galactic latitude was done analogous to the high Galactic latitude case. Obviously, this time the search for appropriate stars does not suffer from their sparse distribution, but rather from their crowding and the larger (and probably differential) reddening.

In Fig. 5 the comparison of GCS-2 with USNO is shown. Again, the difference in both reference magnitudes scatters around zero. This time it becomes apparent that some stars selected by USNO would be too faint when adopting the current magnitude limits in SADT.

Figs. 6 and 7 show the comparison of GCS-2 with UCAC3. Again, the search for UCAC3 was run two times, once without the quality/selection flags (Fig. 6), and once with all flags toggled on (Fig. 7). As can be seen, backtracking was necessary in the latter case, even in this well populated field. Else, the conculsions are very similar as in the high Galactic latitude case: there are much less UCAC3 than GSC-2 stars available and the reference magnitude difference is of the order ~ 0.7 mag.

Finally, in Fig. 8 the comparison of GCS-2 with 2MASS is shown. Notably, there are many GCS-2 stars that have no counterpart in 2MASS. Maybe this can be explained by the cleaner selection criteria with 2MASS. The difference in the R_F and J magnitude now has a very broad distribution over all magnitudes. A simple offset is not applicable in the low Galactic latitude case. Also, when applying the current magnitude limits in SADT to 2MASS most of the selected (valid) guide/aO stars would be too faint in the optical, and thus would cause the OB to fail.

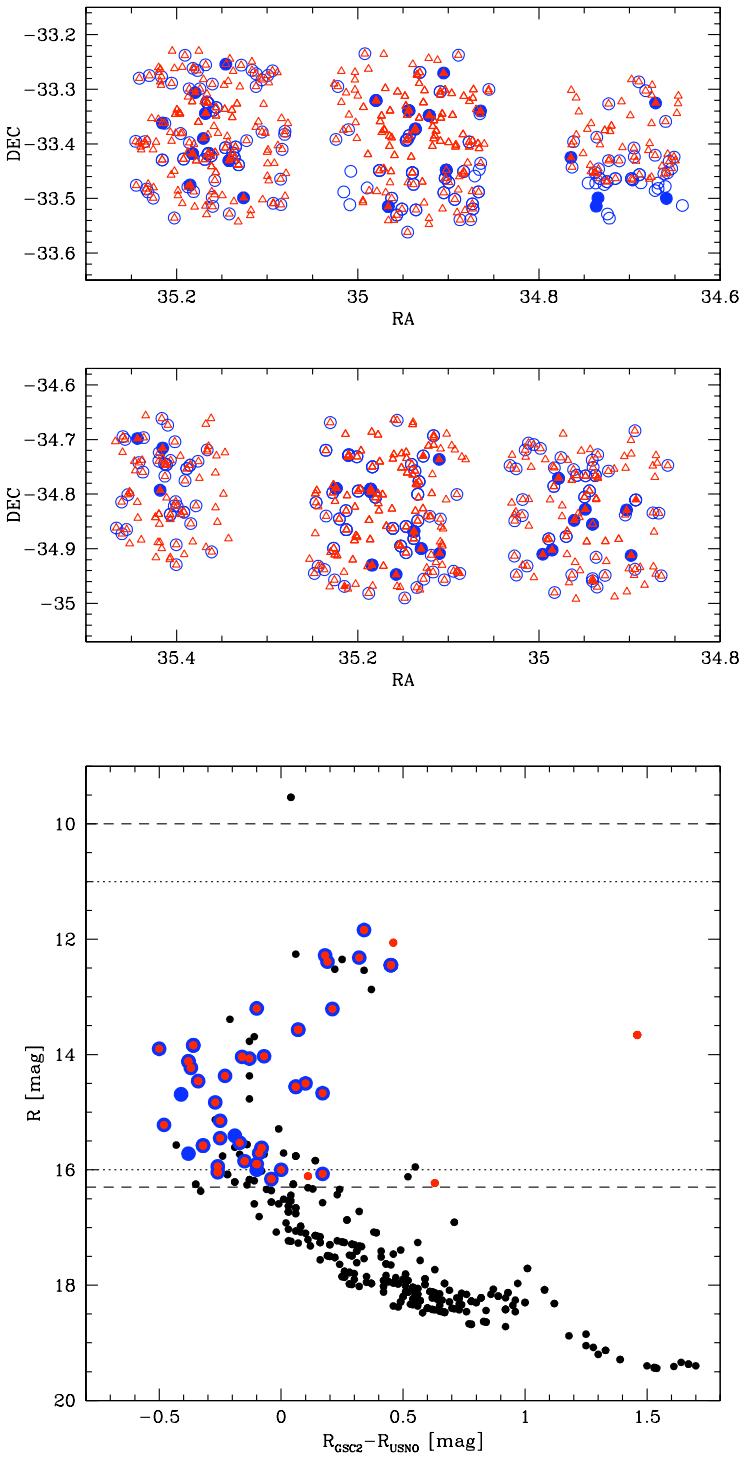

Figure 2: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (blue circles) and USNO (red triangles). Open symbols denote all stars, filled symbols those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid USNO stars.

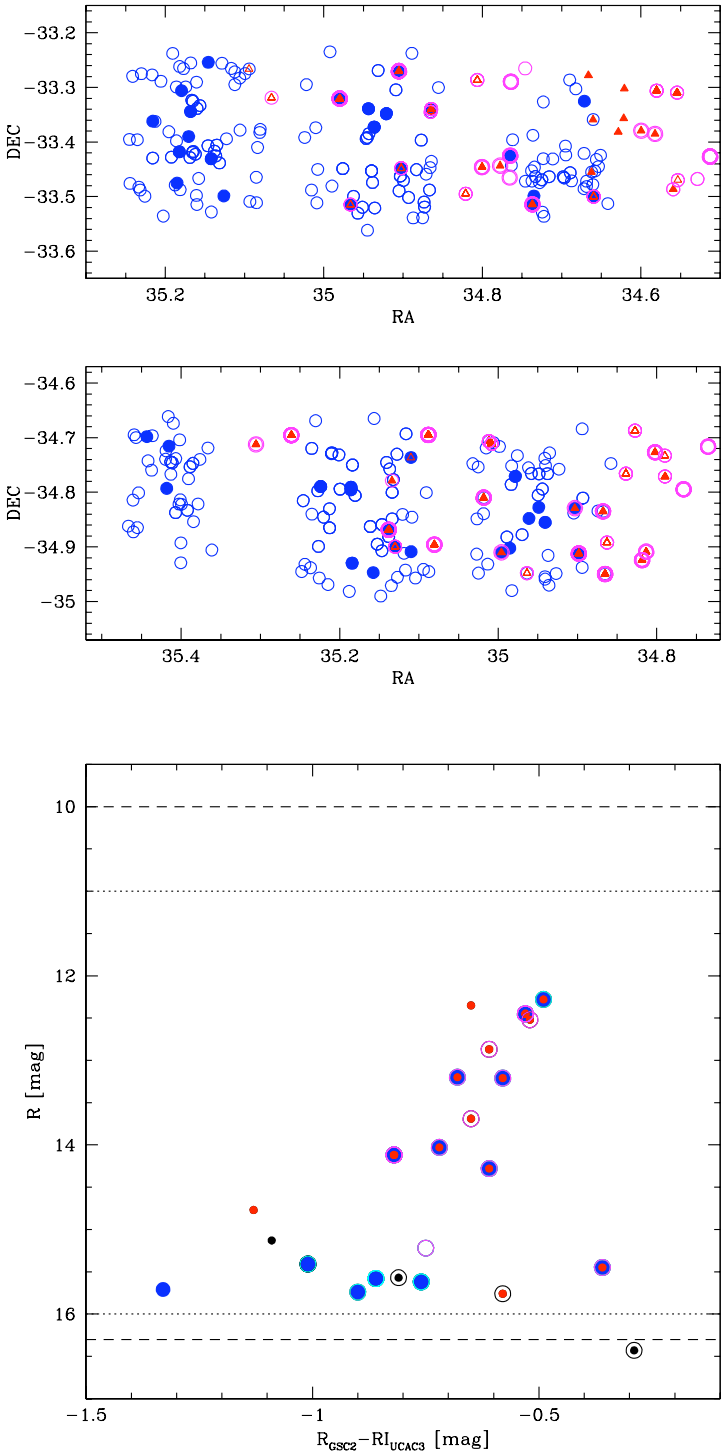

Figure 3: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (blue circles) and UCAC3 (red triangles: selection flags toggled off; magenta circles: selection flags toggled on). Open symbols denote all stars, filled symbols (and the thick magenta circles) those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid UCAC3 stars when no selection flags are applied. Large circles (black, cyan and magenta) denote matches of GSC-2 with UCAC3 applying all selection flags of UCAC3. Cyan circles are valid GSC-2 stars, magenta circles UCAC3 stars.

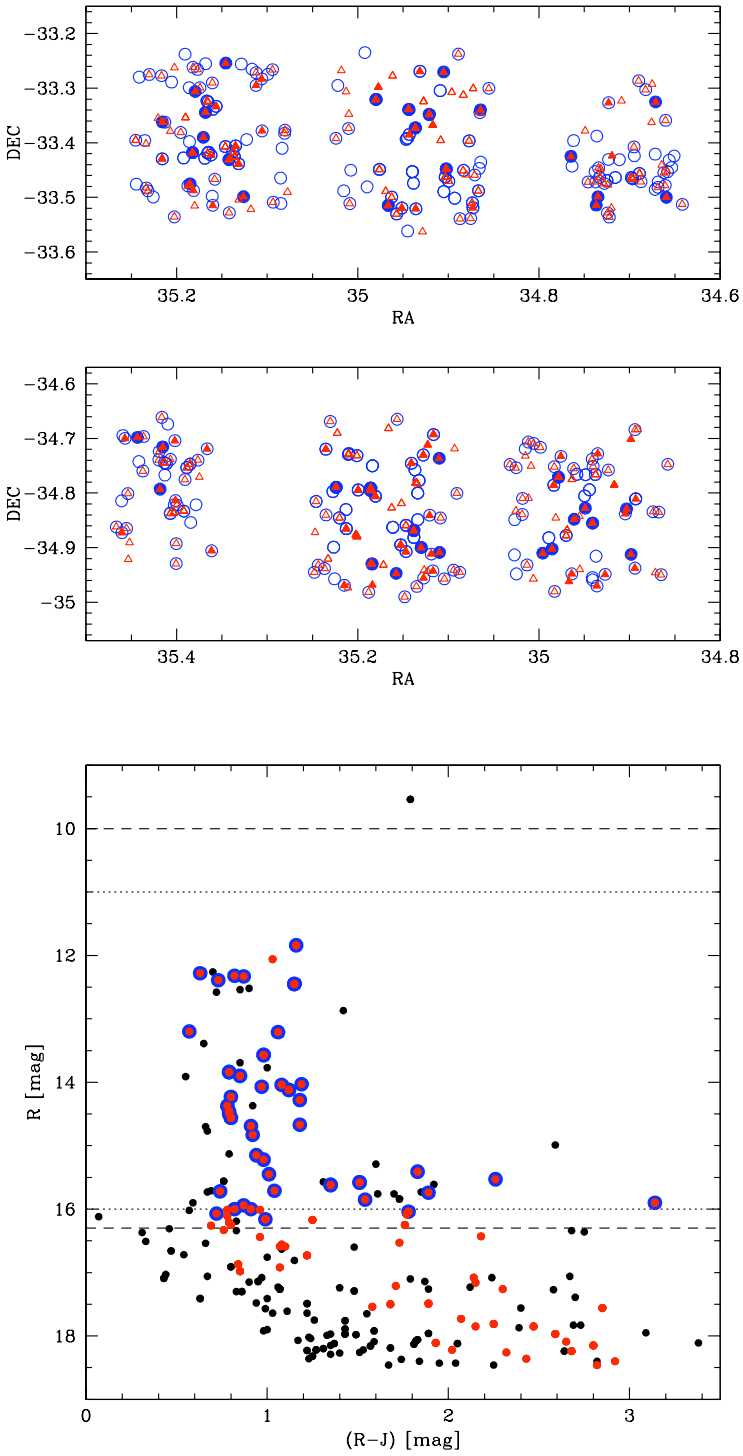

Figure 4: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (blue circles) and 2MASS (red triangles). Open symbols denote all stars, filled symbols those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid 2MASS stars.

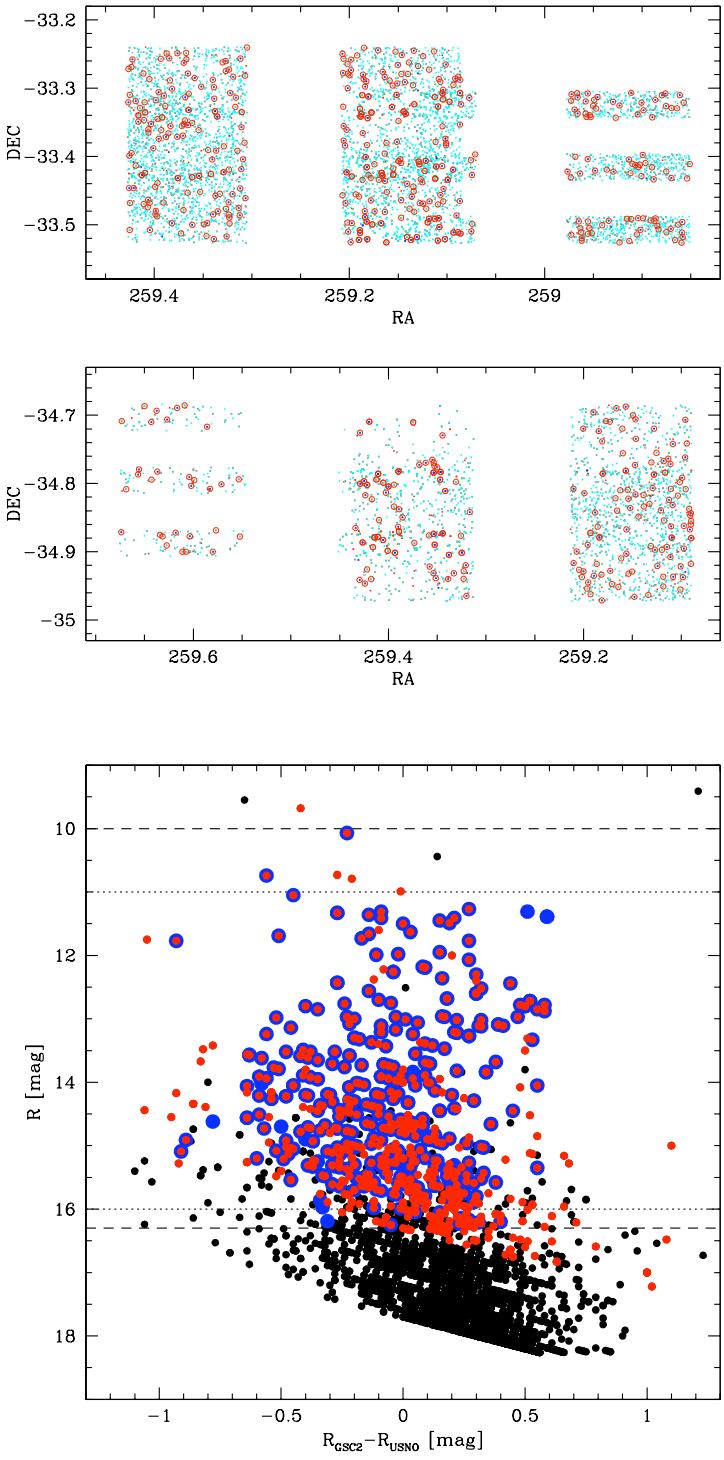

Figure 5: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (cyan/blue) and USNO (red). Cyan and red dots denote all stars, blue dots and red circles those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid USNO stars.

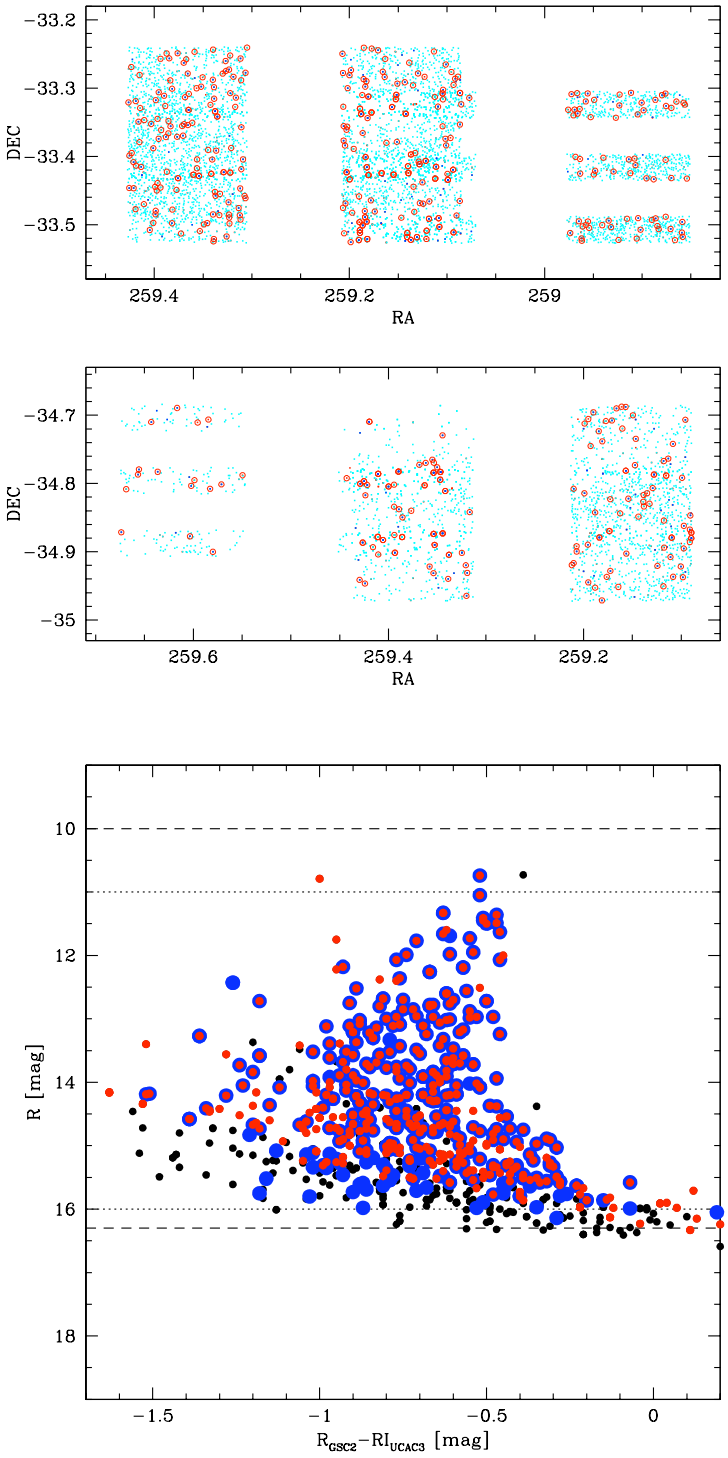

Figure 6: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (cyan/blue) and UCAC3 (red) with UCAC3 selection flags toggled off. Cyan and red dots denote all stars, blue dots and red circles those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid UCAC3 stars.

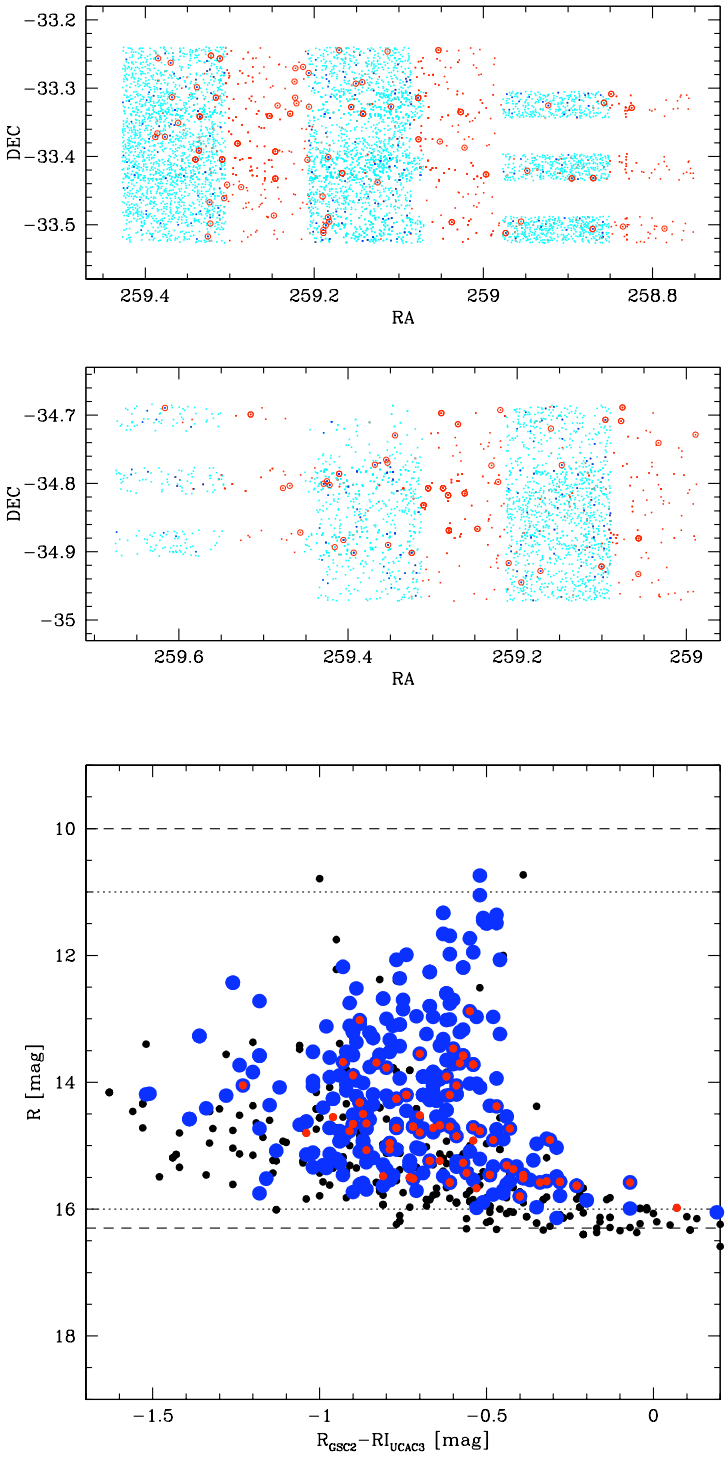

Figure 7: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (cyan/blue) and UCAC3 (red) with UCAC3 selection flags toggled on. Cyan and red dots denote all stars, blue dots and red circles those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid UCAC3 stars.

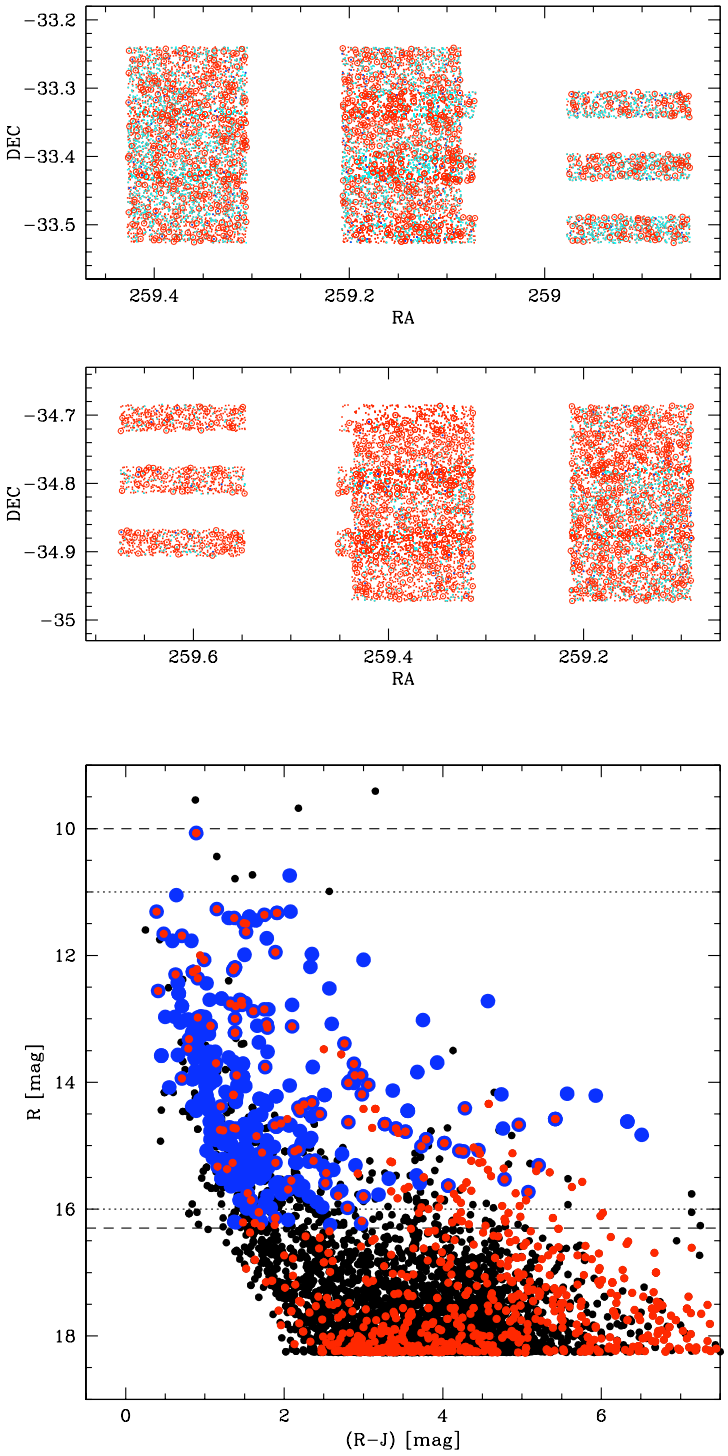

Figure 8: **Upper panels**: position of possible guide/aO stars in the detector regions for GSC-2 (cyan/blue) and 2MASS (red). Cyan and red dots denote all stars, blue dots and red circles those that are valid according to their magnitudes and selection criteria. **Lower panel**: GSC-2 R_F vs. the difference of both reference magnitudes. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid 2MASS stars.

5 The UCAC3 quality/selection flags

UCAC3 has several quality and selection flags that allow to clean the catalog from extended sources, low quality data and false entries. All flags are described in Zacharias et al. (2010, ApJ 139, 2184). The flags that can be toggled on and off in SADT are the following:

Flag	Description	True condition
2MASSID	Checks whether there is an entry in the 2MASS point source catalog	2MASSID > 0
clbl	combination of the SuperCOSMOS 'meanclass' and modified 'blend' flag: 1 = galaxy, 2 = star, 3 = unclassifiable, 4 = noise	clbl = 2
dsf	double star flag used to indicate the type/quality of double star fit: 0 = single star, 1-7 = different cases of double stars or blends	dsf = 0
leda	apparent total diameter from the LEDA catalog (galaxies): 0 = no entry in LEDA	leda = 0
nu1	number of used CCD images	nu1 > 1
type	object type flag: -2 = warning: object could be from possible streak, -1 = warning: object is near overexposed star, 0 = good star, 1 = good star (data copied from another entry), 2 = warning: contains at least 1 overexposed image, 3 = warning: all images are overexposed or 'bad'	type = 0 or type = 1

In order to test which of those flags has most influence on the selection of valid stars SADT was run on one selected tile several times with one flag toggled on (= true condition) at the time and all other flags toggled off (= false condition). The valid stars were then counted and related to the total number of valid stars if all flags are toggled off. The coordinates of the tile were selected such that no backtracking was necessary even with all flags toggled on. Those coordinates are: RA = 18:30.00.0, DEC = -33:00:00.0. The following table shows the results of this experiment. The last row gives the number of valid stars if all flags are toggled on.

Selection	aO stars	%	guide stars	%
All flags false	971	100.0	451	100.0
2MASSID true	953	98.2	438	97.1
clbl true	111	11.4	32	7.1
dsf true	950	97.8	438	97.1
leda true	971	100.0	451	100.0
nu1 true	970	99.9	451	100.0
type true	971	100.0	451	100.0
All flags true	110	11.3	31	6.9

The result is evident. The clbl flag invalidates about 90% of the stars that are in the right magnitude range. This seems not reasonable since visual inspection has shown that also obvious good candidates are rejected by this flag. Probably this flag is wrongly interpreted, and thus the condition clbl=2 is too restrictive.
The next most important flags are the 2MASSID and double star flag dsf which reject about 2-3% of the available stars each which seems a reasonable number. The flags leda, nu1 and type basically have no influence on the rejection of stars.

This kind of experiment can also be used to compare the different catalogs with each other, also with regard to more suitable magnitude limits for UCAC3 and 2MASS. The default magnitude limit in SADT is $10.0 < R < 16.3$ mag for guide star and $11.0 < R < 16.0$ for aO stars. In the following table results are also given for new magnitude limits for UCAC3: $10.7 < R < 17.0$ (guide stars) and $11.7 < R < 16.7$ (aO stars); and new limits for 2MASS: $9.0 < R < 15.3$ (guide stars) and $10.0 < R < 15.0$ (aO stars). Those limits are motivated from the results of Sect. 4.1. The number of all stars, valid+invalid (=out of magnitude limits) is also given as reference how deep the individual catalogs are.

Selection	aO stars	guide stars
UCAC3 (valid+invalid)	2454	859
UCAC3 (valid, flags false)	971	451
UCAC3 (valid, flags true)	110	31
UCAC3 (valid, new mag limit, flags false)	1574	591
UCAC3 (valid, new mag limit, flags true)	178	48
GSC-2 (valid+invalid)	8687	3268
GSC-2 (valid)	1189	425
USNO (valid+invalid)	16869	6641
USNO (valid)	742	312
2MASS (valid+invalid)	6390	2810
2MASS (valid)	1526	719
2MASS (valid, new mag limit)	999	427

This exercise confirms that USNO is the deepest catalog followed by GSC-2, 2MASS and UCAC3. When applying the new magnitude limits to UCAC3 and 2MASS the number of valid stars n these catalogs becomes comparable to that of GSC-2 (with the flags toggled off for UCAC3).

The conclusion of this section is that the magnitude limits for UCAC3 and 2MASS have to adjusted in SADT and that the clbl flag for UCAC3 should be always toggled off. All other UCAC3 flags seems to make sense.

6 Applying the Piskunov formula to the test fields

As mentioned in Sect. 3, Piskunov et al. present in their paper *"Optical Extension of the 2MASS Infrared Catalog"* a procedure for transforming the 2MASS NIR magnitudes to the R-band equivalent magnitude R_J. As input the J, H magnitudes and Galactic coordinates l, b of the star have to be known. This transformation is based on a match of 2MASS with UCAC2. Note that the optical colours in UCAC2 are not very accurate.

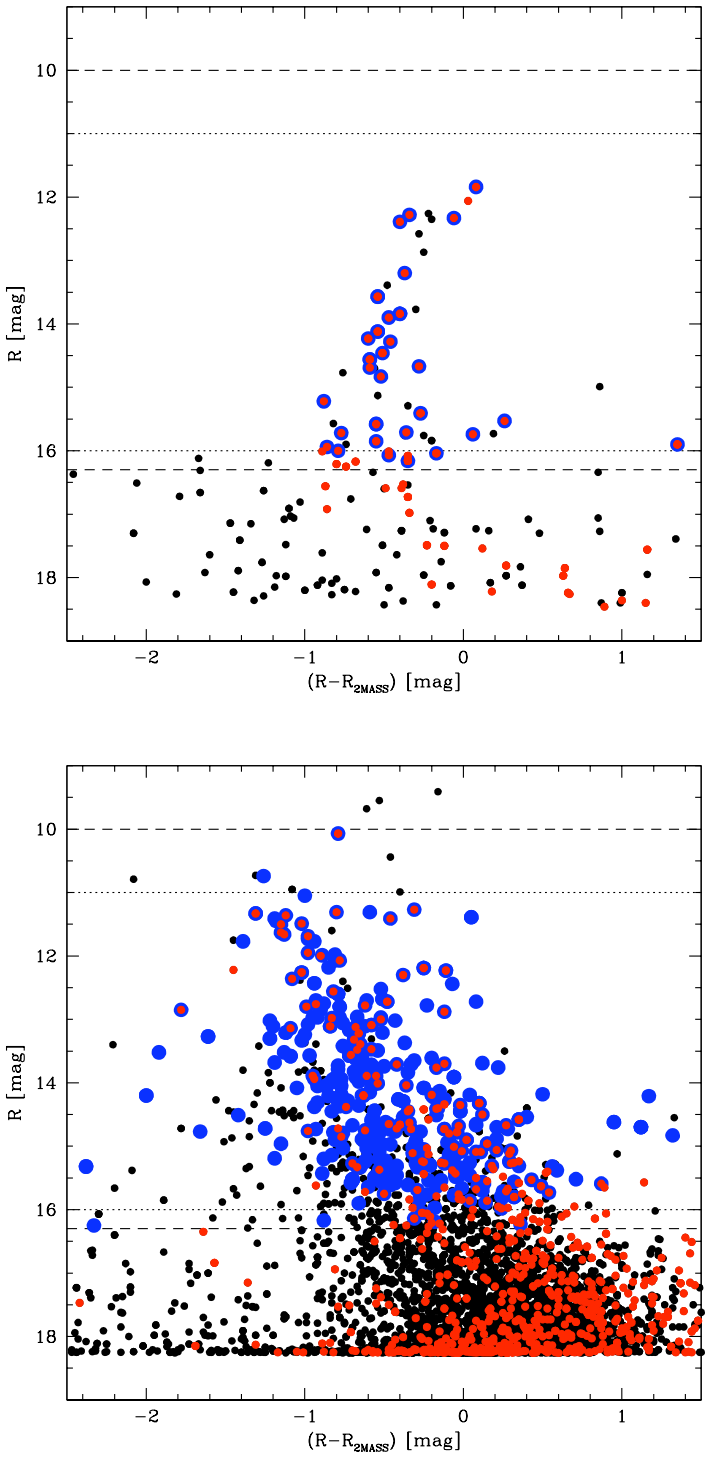

Figure 9: **Upper panel**: GSC-2 R_F vs. the difference $(R_F - R_{J,2\mathrm{MASS}})$ for the high Galactic latitude field. Black dots are stars in common in both catalogs but invalid as guide/aO stars. Large blue dots are valid GSC-2 stars, red dots valid 2MASS stars when applying the same magnitude limit as for R_F to J. **Lower panel**: The same for the low Galactic latitude field.

In order to test whether the R_J magnitude could be used to define the magnitude limits of guide/aO stars in SADT, the Piskunov formula was applied to the two test fields introduced in Sect. 4. Valentin Ivavnov kindly provided a C code that calculates R_J from an input file with the columns Galactic longitude, latitude, J, σJ, H, σH, Ks and σKs. Since the SADT output log only provides the J magnitude, 2MASS catalogs for rectangular regions around the positions of the auxiliary detectors were downloaded from Vizier and matched with the SADT output.
In Fig. 9 the difference between R_F from GSC-2 and R_J from 2MASS is shown for the high and low Galactic latitude fields. As can be seen, this difference does not scatter around zero, thus R_F and R_J are not exactly equivalent. An offset of ~ 0.5 mag would have to be applied to the equivalent R band magnitude of 2MASS in SADT. Fig. 10 shows that the skewed distribution of valid guide/aO stars in the J vs. $(J-H)$ CMD is somehow 'rectified' in the R_J vs. $(J-H)$ CMD, allowing to apply a magnitude cut in R_J. Still an additional colour cut in $(J-H)$, i.e. $(J-H) < 0.8$, might be necessary to avoid too red and faint guide/aO star from 2MASS.

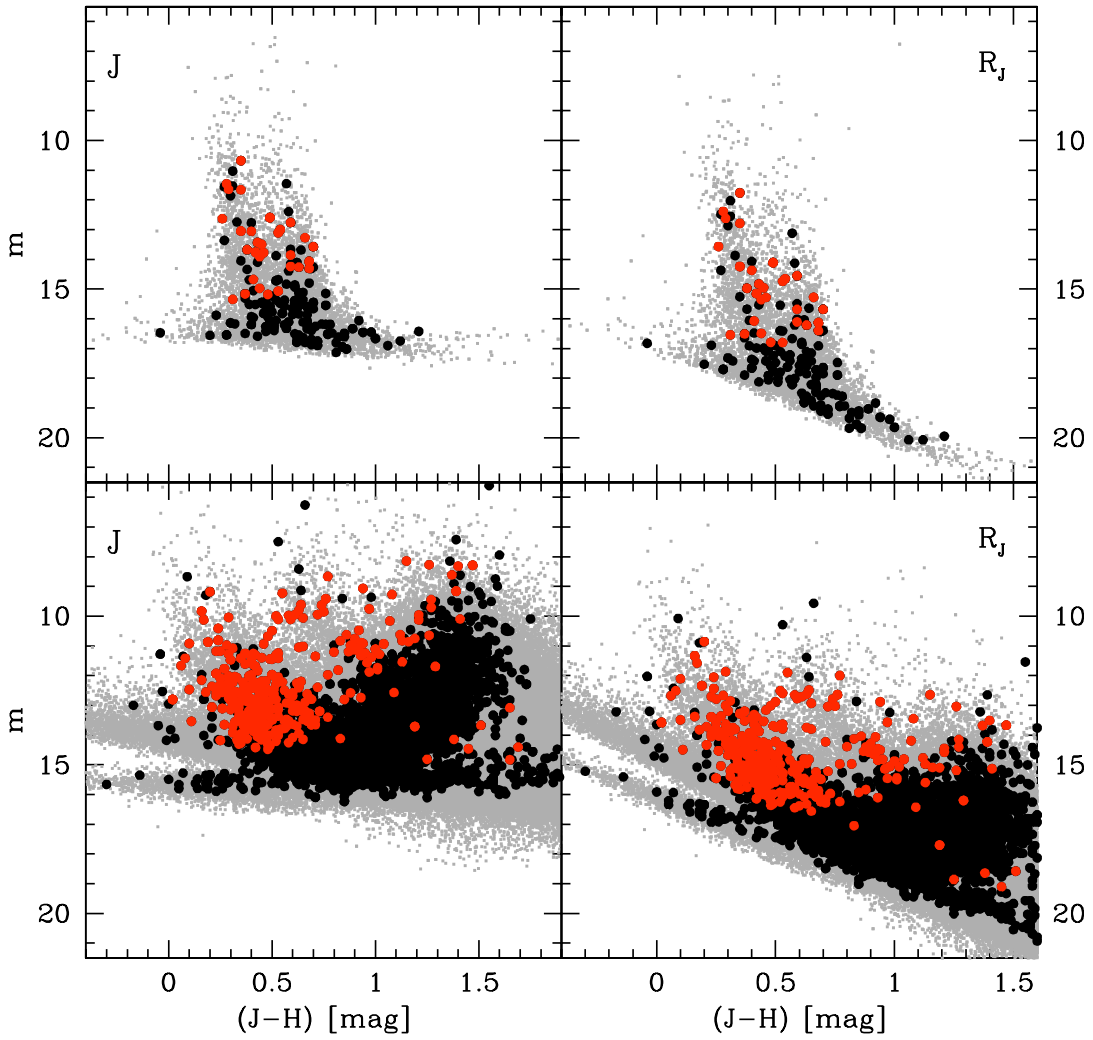

Figure 10: J vs. $(J-H)$ (left panels) and R_J vs. $(J-H)$ (right panels) CMDs for the high (upper panels) and low (lower panels) Galactic latitude fields. Grey dots are all stars from the 2MASS catalog in the regions of the auxiliary detectors. Black dots are those from the SADT log files and red dots the valid guide/aO stars for the GSC-2 catalog.

7 Lessons learned, recommendations, next steps

The past experience with guide/aO star problems at the telescope and this present study of the catalogs has demonstrated that the selection of guide and aO stars has to be improved. None of the catalogs is perfect. In the following the main advantages and deficiences of the four catalogs are summarized:

- **GSC-2:** in principle, a very suitable, rather complete catalog for which the current magnitude limits work more or less. Drawbacks: there exist false entries in regions of scratches, bright targets and crowded fields. Also there are some extended sources and double stars that are not cleaned from the current catalog and enter as valid guide/aO stars. Moreover, the current faint magnitude limit for aO stars (16.0 mag) seems to be too relaxed. Stars with magnitudes > 15.7 mag failed.

- **USNO:** the magnitudes are very similar to those of GSC-2, however with a rather large scatter, questioning the accuracy of the catalog magnitudes. Also USNO is known to be not complete. Crowded regions, bright and extended sources are avoided.

- **UCAC3:** is shallower than GSC-2 and has much less entries even at brighter magnitudes (it is somehow over-cleaned). The CLBL flag is not correctly applied in SADT. It should not be used. The magnitude difference between GSC-2 and UCAC3 is of the order ~ 0.7 mag, thus the magnitude limits in SADT have to be adjusted to fainter limits.

- **2MASS:** the cleanest and most complete catalog. However it has no translation to optical magnitudes which are needed for SADT and the auxiliary detectors. Thus, the current magnitude limits are not valid and cannot be adjusted by applying a simple offset. This would lead to too faint guide/aO stars that might cause the OB to fail.

Ideally, one should use the 2MASS catalog with calculated equivalent R band (or even better I band) magnitudes that can be derived from the NIR colours as demonstrated, for example, in the Piskunov et al. paper. The coding of the Piskunov formula is not a difficult task. Valentin Ivanov managed to create a C code within a few hours that successfully works on a test catalog (see also Sect. 6). Additionally to magnitude limits on the equivalent R band magnitude one might also apply a colour criterium to avoid to red stars in the $(R-J)$ or $(J-H)$ colour. There are several ways how the equivalent R band magnitude can be implemented for use within SADT:

- The formula will be implemented into the code of SADT itself. Thus, whenever the 2MASS catalog is queried, SADT calculates the equivalent R band magnitude (and maybe $(R-J)$) for each star and then applies the appropriate magnitude (colour) limits to select valid star. However, it has to be shown how this calculation would affect the performance of SADT, maybe slowing down the search considerably.

- Ask ESO/SDD to implement the extended 2MASS catalog (including proper motions and the equivalent R band magnitude) into the ESO skycat system. However, this might be a long procedure since no manpower is available on a short timescale.

- Ask CASU to maintain a dedicated catalog based on 2MASS + proper motions + equivalent R band magnitude + colour cuts.

- Ask CDS/Vizier to implement an extra column (the equivalent R band magnitude) for 2MASS on their server. However, it is not clear they provide such a service.

As discussed in the VISTA IOT meeting on November 24th, 2010, even more appropriate would be a formula that transforms the 2MASS colours into equivalent I-band magnitudes. In order to calculate this the overlap region between 2MASS and the SDSS can be used. The drawback is that the overall sky dependence on reddening can only partially be taken into account. CASU has volunteered to provide the colour terms and reddening dependence for this transformation to Jim Emerson. The implementation, however, cannot be provided for the period P87 but will have to be posponed to P88.

References and applicable documents:

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– Michael Hilker (based on work at Paranal in Oct/Nov 2010) –