The SKYGRID Project – A Calibration Star Catalog for New Sensors

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1. EXECUTIVE SUMMARY

New sensor programs for Space Situational Awareness (SSA) are coming on line in the near future. In order to increase the efficiency and utility of such sensors, it is important to extend existing catalogs of calibration stars so that, ultimately, there is at least one calibration star in each field of view (FOV). (The targeted FOV in our planning is 1 square degree.) If this situation were enabled, then high-cost sensors would become significantly more efficient by not having to slew to standard fields in which there are no high priority targets of interest; the necessary calibrations could be done by observations of stars in each target frame. Collection efficiency would therefore be enhanced by this program.

We offer three phases in this Plan. They are intended provide a logical progression toward the expressed goal of one calibrationstar per FOV. Phase I has a duration of one year and will produce a catalog of stars lying near the Celestial Equator (therefore observable at any time of the year from any location on Earth or in orbit). This catalog will extend the Landolt calibration stars to the SILC 415, SILC 590, and Clear filters. (The original catalog consists of Johnson B, V, R, and I observations.) The brightness measures will be accurate to about ±0.03 magnitude.

Phases II and III will require multi-year collections. In Phase II we will complete observations in a 20 degree wide swath along the equator (about 7,200 square degrees). In Phase III, we will extend the observations across the whole sky.

2. INTRODUCTION

A) Existing Astronomical Catalogs

There are several items that must be considered when trying to extend calibration star catalogs toward an all-sky basis. The first is the extremely large number of observations that must be made. There are approximately 41,253 square degrees in the whole sky. Since the widest FOVs that are currently available to the program are Schmidt telescopes whose FOVs cover approximately 1.7 square degrees, it is not realistic to expect that a program of extension could complete the desired all-sky sample without having a new, dedicated wide-field sensor in the near future.

The best alternative to having an all-sky catalog is to observe a selection of stars located roughly along the Celestial Equator (projection of the Earth's equator outward, hereafter "CE"). Any ground-based or space-based sensor would have access to objects in such a catalog. However, in general, there would not be stars in each FOV – the sensor would have to be slewed between observations of targets and calibration stars.

The astronomical community has faced these same issues, and the most broadly recognized response is the Landolt catalog ([1] and references therein), which contains approximately 1,100 stars ranging in V magnitude from 5.99 to 17.80 in approximately 70 fields lying generally near the CE. Most of the Landolt star magnitudes lie in the range 10 < V < 13, which happens to be extremely useful for calibrating observations of geosynchronous satellites (GEOS) since their magnitudes generally lie in the same range. Fig. 1. shows the distribution of Landolt stars, and the concentration near the CE is quite apparent. In general, Landolt concentrated on large numbers of stars in Kapeyn's Selected Areas, which are strongly concentrated toward the CE. However, in order to add stars with a greater variety of colors, he extended his catalog to some isolated objects located relatively far from the CE.

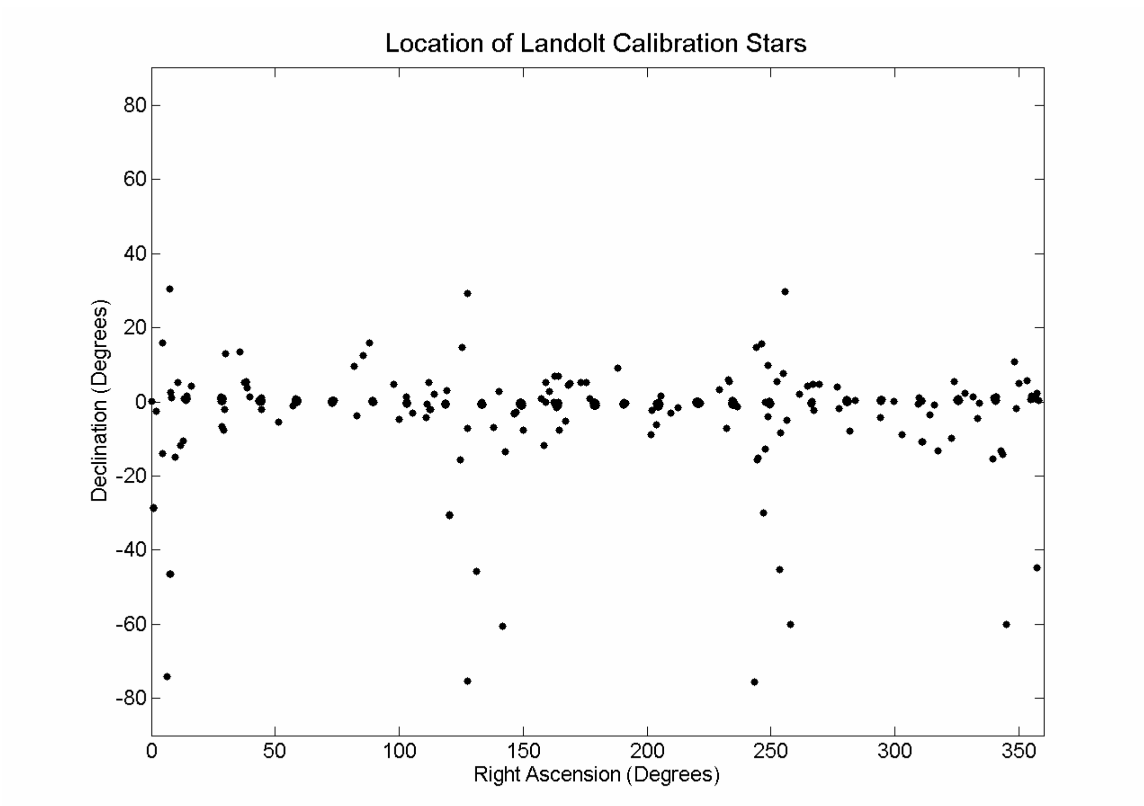

Fig.1. The distribution of Landolt standard stars in the sky. Note the concentration toward the Celestial Equator (Declination = 0^{o}).

There is a useful subset of the Landolt standards – one that is in wide circulation and was originally defined by Dr. Arne Hendren at the US Naval Observatory, Flagstaff Station (NOFS). The Hendren subset lists 29 fields, and the magnitudes originally given in these fields by Landolt have been revised by Hendren, so it represents a smaller, but more accurate, calibration star catalog. Accuracies are approximately ±0.02 magnitudes for individual stars.

We note one useful feature of the Landolt and Hendren catalogs. There are sufficient numbers of observations of each field for the authors to be able to reject variable stars. This important feature will enter our later discussions since it obviously has dramatic impact on how many observations are needed to extend these existing catalogs.

B) Filters

There are separate traditions in the astronomical and satellite communities. The most common filters used by astronomers are the Johnson UBVRI set along with their extensions toward the near infrared (IR); these extensions are the J, H, and K filters (and some with minor modifications to the original specs). Generally similar filters have also been designed by Bessell, Mould, and Gunn, for example.

In the satellite community, there has been a tendency toward using a clear aperture in which the wavelength response of the detector serves as the only "filter". We will refer to such observations as using a "Clear" or "Open" filter. The reasons for using only an Open filter lie in both simplicity of focal-plane optics and the ability to reach fainter limits in less time than is possible with bandpass filters. However, the price that is paid by not using filters is the loss of potentially important information caused by differing reflective properties (i.e. colors) from different materials or from aging and weathering effects. The loss in information resulting from use of the Open filter induces a loss in discrimination capability for programs that rely solely on unfiltered data. The effect is especially dramatic in cases where the objects are spatially non-resolved.

In addition to their having decades of experience in using the standard astronomical filters, the authors have also designed a filter set that optimally emphasizes the differences in reflectivity of GEOs; the filters therefore discriminate among satellites better than the Johnson filters do. (The Johnson filters were designed to discriminate among stars.) The new filter set was part of the Space Object Identification In Living Color (SILC) program, and they are referred to as the SILC filters. Six were originally defined, but only three are now in common use. These include the S415 filter whose central wavelength is 415 nm with a width of 20 nm. The S590 filter has a similar naming convention and the same width. The S850L filter has a short wavelength cutoff at 850 nm and is a long pass filter. It is very similar to the Johnson I filter, and the two can often be interchanged without significant loss of detail.

C) Projected Numbers of Stars

For the purposes of this project, an unfortunate truth is that the number of stars per square degree (hereafter, "density") is highly non-uniform. This, of course is a result of our position in the Milky Way Galaxy. When we look along the great circle of the galactic plane, the density is quite high, but when we look toward the poles the density is low. [We will demonstrate this effect in Sections D i) and D ii).] Additionally, the number of stars at a given magnitude is a non-linear function in which there are many more faint objects than bright ones. Let us look into these issues in more detail by examining Table 1, which provides a rough estimate of the number of stars at each magnitude. Column 1 is the magnitude; column 2 is the number of stars of that magnitude per square degree, and column 3 gives the total number of stars of that magnitude in the whole sky.

Table 1 – Relative Numbers of Stars of Different Magnitudes

Magnitude	**Number/sq. Deg.**	**Number in Whole Sky**
0.0	0.0000794	3
2.0	0.001	41
3.0	0.0037	152
4.0	0.0125	515
5.0	0.0389	1,604
6.0	0.117	4,826
7.0	0.347	14,310
8.0	1.00	14,240
9.0	2.82	116,300
10.0	8.13	335,300

11.0	21.88	902,400
12.0	57.54	2,370,000
13.0	147.91	6,100,000
14.0	363.08	14,970,000
15.0	870.96	35,880,000

We see from the table that at about 8th magnitude, there is approximately the same number of stars as there are 1 degree FOVs in the sky. Unfortunately, there are two problems with this. First, 8th magnitude stars are not appropriate calibrators for those projects and sensors which are observing deep space objects of 11th magnitude or fainter. Secondly, the extremely non-homogeneous nature of the true stellar density means that most 1 degree FOVs will not actually have an 8th magnitude star in them.

D) Data From Test Observations

For Phase I, we have proven data collection and data reduction methods. However, for the more extensive Phases of this program, we need to develop more automated collection and reduction means. The following discussion outlines our preliminary strategy.

i) Maps and Magnitudes

In 2006 some test exposures were obtained for us using a sensor an FOV of approximately 1.3 degree squared (approximately 1.7 square degrees). The observations were done through B, R (although a variant on standard Johnson R), S415, S590, and S850. We have analyzed two fields for the purpose of illustrating the details of this plan and for an assessment of how we need to develop new techniques. The two images are both 5 second exposures in R and were centered on the Landolt fields SA98 and RU149. SA98 is within a degree of the CE, and RU149 lies 34^{o} north of the plane.

Our analyses of these two fields arose from three questions – 1) How well can we identify and measure the magnitudes of the stars in the image? 2) How well can we measure the positions of the stars in the image? 3) How many stars are in the images.

The process of answering these questions poses a test of our computer methods for data reduction. We have recently developed an automated technique for finding and measuring stars. The software for the SKYGRID project will be an evolutionary development of existing programs. Therefore, success at this stage is a bonus in the sense that our basic methods will be easily extensible to a larger project.

In the SA98 field, we found 2,038 stars that satisfied our automatic search criteria. A map of these stars is shown in Fig. 2. in pixel coordinates on the image. Larger markers are used to indicate brighter stars, so it is a “false” map. Only 1,870 stars were actually measured because we rejected measurements of objects too near the edges of the field.

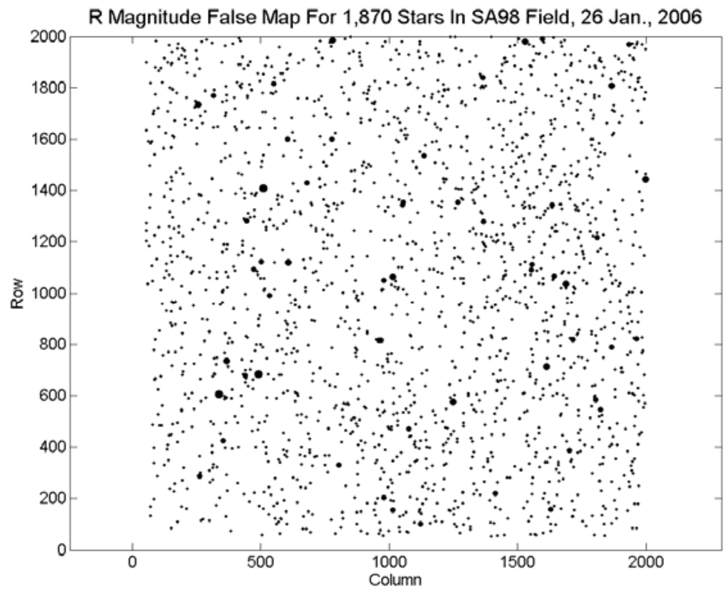

Fig. 2. A map, in pixel coordinates, of the potential calibration stars measured in SA98.

Additionally, in Fig. 3. we show a histogram of the magnitude distribution for the 1,870 measured stars. We note that the peak of the distribution lies in the "sweet spot" for GEOs measurements.

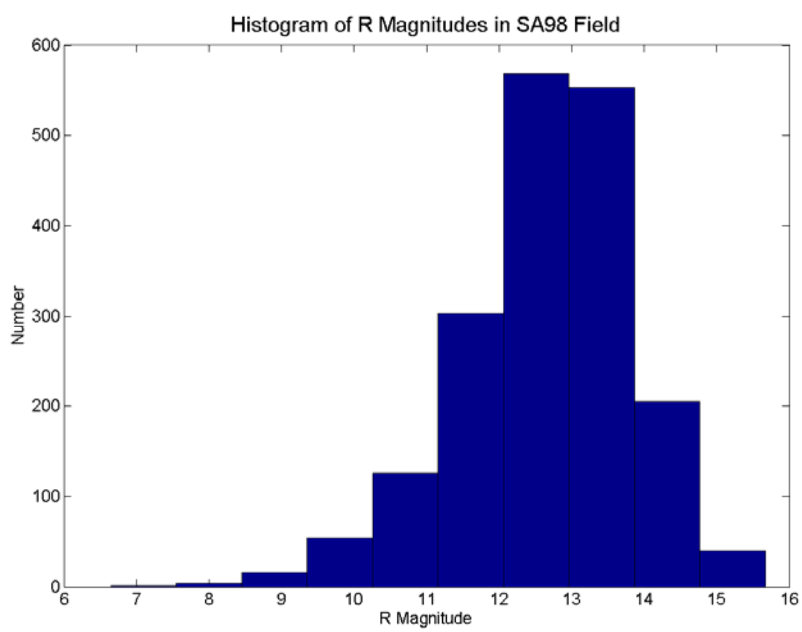

Fig.3. Histogram of the distribution of R magnitudes in calibration star field SA98.

ii) **Metrics**

Comparison of the known accurate positions of the individual Landolt stars (as provided by Hendren) with the positions calculated by our software showed an offset of about 21 seconds of arc. Since this was found to be a uniform difference, we have complete confidence of our ability to find accurately the positions of the stars located in our test frames. This is an important consideration because we will have to base the catalogs that we create on the stars' positions. The offset is likely to be a result of a slight error in the position of the center of the image (i.e. telescope position) as reported in the FITS headers.

iii) Results from the second field

A similar analysis for the RU149 field yielded 244 stars, thus showing the decrease in stellar density at a galactic latitude of 34^o. The distribution and metric accuracy are essentially the same as in the SA98 field.

3. PHASE I PLAN DETAILS

A) General Goals

We propose this Plan with the view that some new sensor programs will wish to make brightness observations through color filters and that the Open filter option needs an improved calibration star catalog. From the discussions given above, we believe that the best way to extend calibration star catalogs for new sensors is progressively to observe larger numbers of fields in the Johnson, SILC, and Open filters. The first extension is Phase I, in which we will observe all the Landolt fields.

Specifically, our first priority is to observe the Hendren subset of the Landolt catalog with an accuracy of ±0.03 magnitudes in the S415, S590 and Open filters. Additionally, there is a possibility of a useful, new filter that would be designed for Solar System observations. The specifications for this filter are currently being developed. If this Solar System filter becomes available within the time frame of our program , we will use it to observe the calibration stars also. If there is the opportunity then we will extend these observations to all 1,100 stars in the Landolt catalog.

B) Observations

The observations will come from several different optical systems. Since Landolt and Hendren have laid the basis for this catalog, an important part of the work is already done. We know which stars in the fields are non-variable. Therefore, we need only observe each star often enough to establish its magnitude in each filter with the accuracy goal of ±0.03 magnitude. Each field will be observed a minimum of three times in each filter. Some fields will be observed more often in order to determine atmospheric extinction coefficients, possible color transformation terms, etc.

4. PHASE II PLAN

In Phase II, we would survey the 7,200 square degree region defined by the 20 degree-wide strip along the CE. We estimate approximately 600,000 stars to be found in this area with magnitudes brighter than m = 13.0.

In order to survey such a large area, a wide field sensor of the 1-meter aperture Schmidt class would be preferred. Our participation would require 25% to 50% of the time on such a telescope for a duration of 2 to 3 years. An important aspect of Phase II is that the variability of the catalog stars is not know, *a priori*. We will have to measure each star several times (current goal is 10 times) in order to assess variability.

For Phase II, we thought it critical to perform the analysis presented in section I. D, above, extending the reduction methods to larger FOVs and crowded fields. Data processing time will need to be addressed. Current data processing algorithms and data bases will evolve in order to meet these new processing demands.

5. PHASE III PLAN

In Phase III, we would survey all 41,253 square degrees of the sky with approximately 6 million stars. A sensor with an FOV of 10^o or greater would be needed. There would also have to be continued evolution of data processing and database capabilities.

6. DISCUSSION

We have outlined an ambitious plan to extend catalogs of photometric calibration stars. Phase I is well underway; it will provide a complete sample of magnitudes for Landolt and/or Hendren stars in the SILC 415 and 590 filters, along with Clear filter observations. Phases II will extend this work to a 7,200 square degree strip along the CE, and Phase III will cover the whole sky.

7. REFERENCE

1. Landolt, A. U., *UBVRI Photometric Standard Stars In The Magnitude Range 11.5 < V < 16.0 Around The Celestial Equator*, Astronomical Journal, Vol. 104, 340-371, 1992

8. ACKNOWLEDGMENT

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