A NEW ALL-SKY REFERENCE STAR CATALOG WITH VARIABILITY DATA

Wayne H. Warren, Jr.
Raytheon Technical Services Company
Laboratory for Astronomy and Solar Physics
NASA Goddard Space Flight Center
Greenbelt, MD 20771

Christopher B. Sande
Alvin C. Miller
Allen T. Home
Computer Sciences Corporation
7700 Hubble Drive
Lanham-Seabrook, MD 20706

David A. Tracewell
Flight Dynamics Division
NASA Goddard Space Flight Center
Greenbelt, MD 20771

Presented at the 87th Annual Meeting of the AAVSO, October 31, 1998

Abstract

This paper describes the current status of the *SKY2000 Catalog* and outlines plans for future improvements. This (SKY2000, Version 2) and future editions of the catalog will be made available on Goddard's Flight Dynamics Division website: http://fdd.gsfc.nasa.gov/attitude/skymap.html.

1. Introduction

The original *SKYMAP Master Star Catalog* (MC) (Gottlieb 1978) was developed to support fixed-head star trackers (FHST) in spacecraft attitude determination software developed at the National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center (GSFC). The first edition was designed as a compilation of stellar objects that would be essentially complete to a blue and visual magnitude of 9.0. Successive versions of the SKYMAP catalog were issued between the years 1978 and 1995 (McLaughlin 1983; Slater *et al.* 1995) to correct individual errors discovered in each interim, but the basic catalog content and format remained the same.

The development of more accurate star trackers in the late 1980's and, especially, of charge-coupled device (CCD)-based detector systems, resulted in a decision to prepare an updated catalog that would include magnitude and color data in the near-infrared (IR). However, several other factors, including the availability of vastly superior and more abundant primary data, the presence of many "derived" data in the old SKYMAP, inadequate and sometimes erroneous cross-identifications, and lingering errors for individual stars (especially multiple systems), led us to redesign and build a new catalog.

2. Data content

The present MC, now renamed the *SKY2000 Catalog*, Version 2, contains almost entirely new primary data (astrometry, photometry), mostly as a result of incorporating information from the European Space Agency's (ESA) Hipparcos and Tycho experiments aboard the Hipparcos satellite. This has helped us to improve the error information for wide-band photometric data and to solve many outstanding "problem" cases. We have also added observed CCD star-tracker data from the RXTE satellite for 4572 stars, and plan to add more.

Version 2 includes 299,099 star entries, all of which have high-quality positions (uncertainty ≤ 1.5", 95.0 percent with uncertainties <0.10"). The vast majority of the entries have Johnson *V* passband magnitudes (99.3 percent). (See Sande and Home 1999 for detailed statistics regarding the SKY2000 Version 2 MC.) All catalog entries have unique identifiers, including a recently-added International Astronomical Union (IAU) standard identifier based on the truncated position. As in past versions of the MC, the latest version includes numerous catalog cross-reference identifiers, spectral type and luminosity class information, and specialized data for double/multiple and variable stars. Also included are radial velocities, photometric data in *UBVRI* and in a special star-tracker CCD band, and positional data in easy-to-use geocentric inertial (GI) unit vector form.

We have reviewed the data content of the current version of the MC only briefly here because interested readers and potential users can find detailed descriptions at the website given in the abstract above. We now move on to describe our plans for future enhancements to the SKY2000 Catalog, in which we go into more detail about how the current information can be improved—and why it is important to do so.

3. Future enhancements

Both the MC and its associated software system (still called SKYMAP) are known to have certain deficiencies and areas that can be improved. These improvements would result in an increase in the utility and reliability of the MC when utilized for mission star catalog generation and when used by amateur and professional astronomers. The explosion in the field of star-catalog work created by modern astronomical techniques allows for a great deal of improvement to be made to the MC and requires frequent updates in order to keep data in the MC current.

Below, we briefly review our plans to improve the data content of the catalog. These plans are dependent on continuing financial support, but we are optimistic that their implementation will be possible in light of the significant advances and more demanding specifications for spacecraft CCD star trackers.

3.1. Cross-identifications

Although there are numerous cross-identifiers in the MC now, there is room for some improvement. Cross-identifications are critical to any compiled catalog because they allow retrieval of new data from other sources and for data validation when questions arise. Even though we now have high-accuracy positions for most of our stars, we must still retrieve data from sources that contain only certain classical identifiers. Despite elaborate checking procedures that have been established to assist with identification verification, some problems remain, as will be described in this section.

The second *Henry Draper Extension* (HDE) (HD 272151–359083; Cannon and Walton Mayall 1949) was published only in chart form. Thus only sparse cross-identifications with other source catalogs have been made for specific stars over the years. Using the recent work of Nesterov *et al.* (1995), who measured accurate positions for HDE chart stars on paper copies of the original charts, then transformed them to J2000, we can cross-identify SKY2000 stars with HDE identifiers to complete the identification of HD stars in our catalog. This is important because HD numbers are widely used in other source catalogs and in the literature to identify stars for which we may need data in the future.

All *Durchmusterung* (DM, including the BD and CP) supplemental stars (objects having lower-case "a" or "b" appended to their DM numbers) must be reviewed in SKY2000. The lower-case letters have often been omitted from source catalogs in the past, resulting in confusion between supplemental stars and their main-catalog counterparts. (Supplemental stars were inserted as "footnotes" to the original catalogs; thus they are entirely independent, and separate objects from each other. If they become confused, an erroneous identification results.) We also intend to examine stars that have duplicate BD numbers supplemented by "P", "S", and "X" letter designations. These designations are present in the *Positions and Proper Motions* (PPM) catalogs because most are relics from the *Astronomische Gesellschaft* (AG) catalogs. The letter designations are not present in the BD and were assigned by the AG cataloguers if two stars happened to be close to one another on a photographic plate, even if only one of the objects actually had a BD number. These stars are often not even present in the *Washington Catalog of Visual Double Stars* (WDS) (Worley and Douglass 1997), meaning that both stars should not have the assigned BD number of one of the pair.

To eliminate these "P", "S", and "X" letter designations, which are confusing because of their absence from most other source catalogs and because they are not "official" designations, each pair of objects must be examined to determine which of the two objects is really the BD star. Then the letters can be removed and the BD number can be deleted from the non-BD star. In cases where the "correct" BD star cannot be unambiguously identified, it may be preferable to retain the lower-case letters, although AG identifiers are being inserted for these pairs and those are always different. Approximately 600 SKY2000 stars have "P", "S", or "X" designations, of which roughly half should not have DM identifiers at all, as they just happen to be near stars on photographic plates.

Component assignments for double and multiple systems are not yet complete, nor are they entirely consistent in SKY2000, mainly because of the structural differences between the WDS and SKY2000. Blended flags are not always present for blended pairs because many photometric data were taken from catalogs containing no blending information. While the incorporation of Hipparcos and Tycho data has corrected a large number of these problems, it has by no means eliminated all of the discrepancies and may even have introduced new problems, because the Tycho detectors did not resolve close pairs either. The task of assigning correct component identifiers involves analyzing each double star manually or by machine to determine the separation of the components, whether or not the catalog entry represents more than one object, and what WDS component the entry represents (making the A and B assignments for WDS entries not having letter designations).

There is a special SKY2000 data field for variable star designations. These include the 5th edition of the GCVS (*General Catalogue of Variable Stars*) (Kholopov *et al.* 1995) names for known variables and NSV (*New Catalogue of Suspected Variable Stars*) (Kholopov *et al.* 1982) identifiers for suspected variables. A rather significant number of variable star names were omitted from the name field in the old SKYMAP catalog. The reason for this is unknown, but the situation represents a serious shortcoming and should be corrected, since variable star identification is an important aspect for a spacecraft acquisition catalog. The latest information on variables will be inserted into SKY2000 by processing the 1995 version of the GCVS. We also plan to make use of the AAVSO archives to improve variability data for (mainly) long period variables.

3.2. Astrometric data

Not long after data from the U.S. Naval Observatory's ACT (*Astrographic Catalogue and Tycho*) (Urban *et al.* 1998) and ESA's *Hipparcos and Tycho Catalogues* (ESA 1997) were ingested into the MC, a joint European catalog roughly the equivalent of ACT was released to the data centers. It is known as the *Tycho Reference Catalogue* (TRC) (Høg *et al.* 1998) and, like ACT, it combines century-old *Astrographic Catalogue* data with Tycho data to improve the latter's proper motions by a factor of 10 or more. The accuracies of the ACT and TRC catalogs are comparable (although there is a proper motion standard deviation, σ_μ, of 2.65 mas/a). However, the TRC and ACT catalogs include slightly different subsets of the original Tycho catalog, even though they contain a comparable total number of stars (ACT 988,758; TRC 990,182). In fact, the TRC contains almost 40,000 stars that are not included in ACT, many being fairly close double stars that give us problems in SKY2000. We have replaced some dozens of Tycho positions with positions and proper motions from the TRC during manual analysis and correction of SKY2000 Version 2, and have found that the errors are significantly better for TRC data. We also intend to replace Tycho parallax data with ground-based parallaxes for stars that are in the *Yale Catalogue of Trigonometric Parallaxes* (van Altena *et al.* 1995).

3.3. Photometric data

Photometric data, or brightnesses and colors, are, along with astrometric data, the fundamental information of the SKY2000 catalog, since they are essential for spacecraft attitude determination and positioning. It is important to have not only the most accurate photometric data available, but also to include their mean errors whenever possible, since these contain information on variability and deviations in brightness that might be seen by spacecraft sensors. Although the Tycho mission has provided us with observed photoelectric data (the most accurate kind) for almost all SKY2000 stars, the short baseline of the Tycho photometric observations tend to produce small errors that hide variability. Thus, if high-quality ground-based data that were measured over a significantly longer time period are available with mean errors, it is better to use those. Our preferred hierarchy for photometric data is therefore: use high-quality ground-based data if they are available, observed Tycho data if they are not; derived data based on photovisual and/or photographic magnitudes and spectral types if no observations are available; or even visual estimates if too little information can be found to derive values. In all cases, we wish to have some kind of brightness estimate available and to identify its source and data type, which gives an estimate of accuracy.

There are several different broadband photometric systems that have been developed since the advent of the original Johnson system. The newer systems differ significantly only in the near-IR bands (*R* and *I*), where the Johnson system has difficulties. The astronomical community has essentially abandoned the Johnson system over the last several years and migrated to the Cousins (Cousins 1981) system, which has *R* and *I* filters that are blueward of Johnson's and avoid many of the detector and atmospheric problems of the latter. We would like to replace all Johnson *RI* data in SKY2000 with Cousins system data. Since there are more stars observed in the Johnson system at this point, we will transform stars having no Cousins data from Johnson *RI* to Cousins *RI* if they are in the color range where such transformation is valid (see Bessell 1983).

3.4. Spectroscopic data

MK (two-dimensional) spectral types are an integral part of the red magnitude prediction subsystem that is used to estimate what the CCD star-trackers will see. Many thousands of new MK types have appeared in the literature since the last compilation of MK types (Morris-Kennedy 1983) that contributed data to SKY2000. (More recent compilations of MK types by Buscombe (1995) have become available, but they do not contain bibliographical citations to the original sources. Original references should be given in any compilation of such data in case more information is desired about the data or if disagreements and/or inconsistencies are to be resolved.) The MK types currently in the MC are mainly concentrated in the southern hemisphere because of the sky coverage of the *Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars* (vols. 1–4, covering declination zones -89° to -12°) (Houk and Cowley 1975; Houk 1978, 1982; Houk and Smith-Moore 1988).

3.5. Double and multiple stars

Correct information for double and multiple stars is very important for successful application of the SKYMAP System to satellite attitude determination. The primary goal of the system is to predict what a spacecraft sensor will see when it looks at the sky to determine its orientation. To this end, a mission run catalog is tailored to fit the specifications of the sensor in terms of resolution and brightness detection limits. In other words, double and multiple stars are blended according to their magnitudes, separations, and position angles, to represent what the sensor is predicted to see based on its characteristics. If the double-star data are not correct, then the object predicted by the blending routines will not agree with what the sensor actually sees during the mission. Thus, the ultimate goal of our MC work is to provide accurate data for double and multiple systems valid at a given epoch and, for systems that change because of orbital motion, to include the data necessary to predict what a spacecraft sensor will see at any given time.

The end result of the above requirements is that we need accurate identifications of the components of each multiple system represented by one or more MC entries, plus information about the individual components to enable the software to determine if and how to blend the stellar images for a given detector system. This provides high-quality information on multiple systems for all users of the catalog.

Data for visual binaries having orbits are needed to predict what spacecraft sensors will see at any given epoch for bright pairs of stars with orbital motion. Orbital data from the *Fourth Catalog of Orbits of Visual Double Stars* (Worley and Heintz 1983) and an associated machine-readable file of newer orbits are available in a form that can be processed in a straightforward manner after cross-identifications are made for the systems involved. The only task that may require some analysis is deciding between new orbits in a supplementary file and orbits in the original catalog file for the same system. Most of the time the newer orbits are better, but not always. The data field is already allocated and must only be filled with orbital-period data. However, to compute ephemerides for binary pairs, for example, to predict the separation and position angle at any given epoch (what the star trackers will see) requires information not now present in SKY2000. This information (the elements of the orbit) will have to be ingested from the orbits catalog and will require format modifications to SKY2000 records. However, users of the catalog will benefit from having available all information needed to compute ephemerides of orbiting pairs.

3.6. Variability data

Data for variable stars in the old SKYMAP catalog consisted of periods, epochs, amplitudes, and types of variability, all of these being taken from the GCVS. To predict what a sensor will see at any given time, however, requires that an ephemeris be computed for any given variable in the field of view. While this is not feasible for irregular variables, it can be done for most variable types if sufficient and accurate enough information is available. Since the photometric data for variables consist of a mean of observations for a variety of times, we do not now have enough information to predict a magnitude for any given epoch, even for well-behaved variability. Therefore, we have provided data fields for maximum and minimum magnitudes in Version 2 of the MC. The challenge, by no means a trivial one, is to fill these fields with reliable data. We hope to use the archives of the AAVSO to help at least to partially complete this job, although we realize that there will be many empty fields in the near term.

We also intend to reprocess data in the NSV because we know that some records were not correctly processed for the old SKYMAP catalog. Another problematical situation concerning the NSV is that *V* magnitudes from the GCVS (source 30) and the NSV (source 31) have been mixed with colors from other sources. These data are then combined in the SKYMAP software to compute *U* and *B* magnitudes. For stars that are variable, this procedure is invalid because the magnitudes and colors come from different sources and were observed at different times (epochs). To fix this problem, *V* magnitudes from the same sources as the colors should be put back into SKY2000, and then the *U* and *B* magnitudes recomputed.

4. Summary

A new version of the SKY2000 MC has been prepared to support spacecraft acquisition and tracking applications. The major enhancements in the new version include improved cross-indexing among star designations, almost complete replacement of astrometric data, which are now on the new international system ICRS (International Celestial Reference System) (Feissel and Mignard 1998), propagation of positional error estimates to the current catalogue epoch (2000.0) to make them more realistic, almost complete replacement of derived photometric data with photoelectric observations, improved photovisual and photographic magnitudes throughout the catalog, the correction of many individual errors present mostly for double and multiple stars, and an improved format with more uniform data fields. Future plans call for significant improvements in data content, particularly for multiple and variable stars. We hope to produce a very high-quality compilation of stellar data that will be useful in many areas of astronomy as well as in the original application of spacecraft attitude determination.

References

Bessell, M. S. 1983, *Publ. Astron. Soc. Pacific*, **95**, 480.

Buscombe, W., and Foster, B. E. 1995, *MK Spectral Classifications: 12th General Catalogue, epoch 2000, including UBV photometry*, Dearborn Observatory, Northwestern Univ., Dearborn, IL.

Cannon, A. J., and Walton Mayall, M. 1949, *The Henry Draper Extension (Annie J. Cannon Memorial Volume)*, *Ann. Harvard Coll. Obs.*, 112.

Cousins, A. W. 1981, *Mon. Not. Astron. Soc. Southern Africa*, **40**, 37.

ESA 1997, *The Hipparcos and Tycho Catalogues,* SP-1200, Vol.1, 57, European Space Agency, Publications Division, Noordwijk, Netherlands.

Feissel, M., and Mignard, F. 1998, *Astron. Astrophys.*, **331**, L33.

Gottlieb, D. M. 1978, *Astrophys. J. Suppl.*, **38**, 287.

Høg, E., Kuzmin, A., Bastian, U., Fabricius, C., Kuimov, K., Lindegren, L., Marakov, V. V., and Röser, S. 1998, *Astron. Astrophys.*, **335**, L65.

Houk, N., and Cowley, A. P. 1975, *Michigan Catalogue of Two-Dimensional Spectral Types in the HD Stars* [*MIC*], Vol. 1, Decl. -90° to -53°, Dept. of Astronomy, Univ. Michigan, Ann Arbor.

Houk, N. 1978, *MIC*, Vol. 2, Decl. -53° to -40°, Dept. Astron., U. Michigan, Ann Arbor.

Houk, N. 1982, *MIC*, Vol. 3, Decl. -40° to -26°, Dept. Astron., U. Michigan, Ann Arbor.

Houk, N., and Smith-Moore, M. 1988, *MIC*, Vol. 4, Decl. -26° to -12°, Dept. Astron., U. Michigan, Ann Arbor.

Kholopov, P. N., *et al.* 1995, *General Catalogue of Variable Stars*, 5th ed., Moscow.

Kholopov, P. N., *et al.* 1982, *New Catalogue of Suspected Variable Stars*, Moscow.

McLaughlin, S. F. 1983, *Astron. J.*, **88**, 1633.

Morris-Kennedy, P. 1983, *MK Classification Extension*, Mt. Stromlo and Siding Spring Observatories, Australia.

Nesterov, V. V., *et al.* 1995, *The Henry Draper Extension Charts: A Catalogue of Accurate Positions, Proper Motions, Magnitudes and Spectral Types of 86933 Stars*, *Astron. Astrophys. Suppl.*, **110**, 367.

Sande, C., and Home, A. 1999, Star Catalog Analysis Report: S*KYMAP SKY2000 Version 2 Master Catalog Data*, Computer Sciences Corp., internal report.

Slater, M.A., Jr., Miller, A.C., Warren, W.H., Jr., and Tracewell, D.A. 1995, in *Astrodynamics 1995, Advances in the Astronautical Sciences*, eds. K.T. Alfriend, I.M. Ross, A.K. Misra, and C.F. Peters. Univelt, Inc., San Diego, CA, **90**, part 1, 67.

Urban, S. E., Corbin, T. E., and Wycoff, G. L. 1998, *Astron. J.*, **115**, 2126.

van Altena, W. F., Lee, J. T., and Hoffleit, D. 1995, *General Catalogue of Trigonometric Stellar Parallaxes*, Yale Univ. Observatory, L. Davis Press, Schenectady, NY.

Worley, C. E., and Douglass, G. G. 1997, *Washington Catalog of Visual Double Stars 1996.0, Astron. Astrophys.*, **125**, 523.

Worley, C. E., and Heintz, W. D. 1983, *Fourth Catalog of Orbits of Visual Binary Stars*, *Publ. U.S. Naval Obs.*, 2nd ser., **24**, part 7.