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THE SOUTHERN PROPER MOTION PROGRAM. IV. THE SPM4 CATALOG

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ABSTRACT

We present the fourth installment of the Yale/San Juan Southern Proper Motion Catalog, SPM4. The SPM4 contains absolute proper motions, celestial coordinates, and B, V photometry for over 103 million stars and galaxies between the south celestial pole and -20° declination. The catalog is roughly complete to $V = 17.5$ and is based on photographic and CCD observations taken with the Yale Southern Observatory's double astrograph at Cesco Observatory in El Leoncito, Argentina. The proper-motion precision, for well-measured stars, is estimated to be 2–3 mas yr^{-1}, depending on the type of second-epoch material. At the bright end, proper motions are on the International Celestial Reference System by way of *Hipparcos* Catalog stars, while the faint end is anchored to the inertial system using external galaxies. Systematic uncertainties in the absolute proper motions are on the order of 1 mas yr^{-1}.

Key words: astrometry – catalogs

Online-only material: color figures

1. INTRODUCTION

The Yale/San Juan Southern Proper Motion program (SPM) is a decades-long undertaking to determine absolute proper motions of southern-sky stars for the purpose of better understanding our Galaxy's structure and kinematics. The SPM was founded as the southern-sky counterpart to the Lick Northern Proper Motion program (see Klemola et al. 1987; Hanson et al. 2004) and has benefited greatly from lessons learned in that venture. The original impetus behind the SPM and its planning and organization are described in detail by van Altena et al. (1990, 1994).

Over the years, the SPM has grown to encompass a diverse set of projects ranging from targeted, optimal-accuracy studies to more general, large-area surveys. Among these are the numerous determinations of absolute proper motions of Milky Way globular clusters summarized by Casetti-Dinescu et al. (2010), with the SPM program being responsible for over half of all clusters in either hemisphere, with well-measured absolute proper motions; a proper-motion study of the Magellanic Clouds (Vieira et al. 2010), in which the large-format, overlapping SPM material allows for a unique measure of the motion of the Small Magellanic Cloud relative to the Large Magellanic Cloud; a determination of the absolute motion of the Sagittarius dwarf galaxy (Dinescu et al. 2005a) and of the Canis Major dwarf galaxy (Dinescu et al. 2005b); a determination of the velocity shear of the Milky Way thick disk (Girard et al. 2006) using a sample of SPM stars at the south Galactic pole; a further investigation of thick-disk kinematics using a larger sample of SPM stars with radial velocity measures (Casetti-Dinescu et al. 2011); and an exploration of possible open cluster remnants via candidate star proper motions (Carraro et al. 2005). More utilitarian uses of SPM material have included confirmation of the precursor to SN 1987a (Girard et al. 1988); identifying the optical counterpart to non-optical discoveries, e.g., GRO J1655-40 (Bailyn et al. 1995); helping to establish the link between the *Hipparcos* system and that of the International Celestial Reference System (ICRS; Platais et al. 1998b); and providing positional input to other proper-motion projects such as the UCAC3 (Zacharias et al. 2010). The raw catalog products of the SPM are a series of astrometric and photometric catalogs of successively expanded sky coverage and completeness. The fourth catalog in this series, the SPM4, is presented here.

In what follows, we provide a brief historical background for the SPM in Section 2 and a description of the observations and measurements in Section 3. Details of the catalog construction, i.e., the astrometric and photometric reductions, are given in Section 4 while Section 5 takes a look at the properties of the resulting catalog. Section 6 provides an overview of previous SPM catalogs to help clarify the relevant differences for the potential user. Finally, an overall summary is given in Section 7 along with information about obtaining or accessing the catalog.

2. HISTORICAL BACKGROUND

In 1960, the Yale-Columbia Southern Observatory, under the leadership of Dirk Brouwer of Yale University and Jan Schilt of Columbia University, was granted $750,000 by the Ford Foundation with the goal of building an observatory to determine the accurate positions and apparent motions of the stars to study the structure of our Milky Way Galaxy from the

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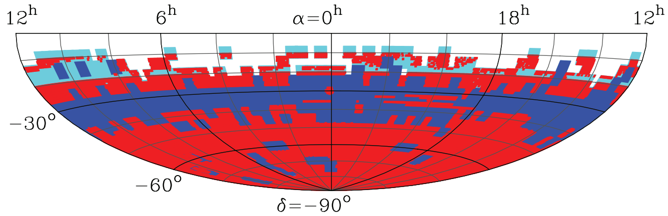

Figure 1. Sky coverage of the SPM surveys, in equatorial coordinates. The light blue area indicates first-epoch plate coverage. Overplotted in dark blue is the area covered by second-epoch photography. Areas with second-epoch CCD observations are shown in red. Second-epoch CCD measures were used for roughly two thirds of the areal coverage of the SPM4 catalog.

(A color version of this figure is available in the online journal.)

Southern Hemisphere. Following a survey of potential sites in Australia, Chile, and Argentina, an observatory was built at El Leoncito, Argentina. The observatory was jointly operated by the University of Cuyo's Observatorio Astronómico "Felix Aguilar" (OAFA) in San Juan, under the leadership of Carlos U. Cesco, Jose Augusto López, and the Yale-Columbia Southern Observatory, Inc. (YCSO).

The first survey of the southern sky, now known as the Yale/San Juan Southern Proper Motion survey, or the SPM, was made between the years 1965 and 1979 under the direction of Adriaan J. Wesselink, Pierre Demarque, and William van Altena at Yale following the death of Dirk Brouwer in 1966. Financial support for the survey was obtained through a series of grants from the US National Science Foundation. Due to changing research priorities at Columbia University, Columbia withdrew from the Corporation in 1974 and the name was officially changed to Yale Southern Observatory, Inc. (YSO) on 1975 January 23. At that time William van Altena joined Yale and assumed the direction of the YSO; he continues to lead the organization and direct the SPM. About two years earlier, the University of Cuyo had split into several regionally based units. The one based in San Juan became known as the Universidad Nacional de San Juan (UNSJ) and it assumed the administration of the OAFA and partnership with the YCSO and then the YSO. After Carlos E. López arrived at the OAFA in 1980, he assumed responsibility for the YSO operations in Argentina and continues in that role. Subsequent directors of the OAFA and Rectors of the UNSJ made substantial contributions to the progress of the SPM. In 1990, the El Leoncito Observatory was renamed the Dr. Carlos U. Cesco Observatory on the occasion of the 25th anniversary of the beginning of observations in honor of Dr. Cesco's many contributions to the founding and operation of the Observatory.

3. OBSERVATIONS AND PLATE MEASUREMENT

SPM observations have been carried out using the 51 cm double astrograph of the Cesco Observatory in El Leoncito, Argentina. The double astrograph is essentially two telescopes sharing a common structural assembly and mount. One of the two objective lenses is optimized for the visual passband; the other is optimized for blue. The photographic portion of the SPM survey was taken on quarter-inch thick 17 × 17 inch plates, 103a-G emulsion with an OG515 filter for the yellow lens and unfiltered 103a-O emulsion for the blue lens. The first-epoch survey, taken from 1965 to 1979, is entirely photographic. The second-epoch survey is approximately 1/3 photographic (taken from 1988 to 1998) and 2/3 CCD-based (taken from 2004 through 2008). Figure 1 shows the survey coverage differentiated by second-epoch detector type. The survey consists of fields at 5° centers in declination and varying offsets along right ascension, but always less than or equal to 5°. Since each photographic plate covers a 6.3 × 6.3 deg area of sky, there is significant overlap in the photographic portion of the survey. Also, each field has a pair of blue and yellow passband plates taken (typically) simultaneously with the double astrograph. For a small fraction of the fields, plates were repeated within the same "epoch." Each photographic observation consisted of two offset exposures, one 2 hr in duration and the other 2 min in duration. All photographic exposures were centered on the meridian. An objective wire grating, with grating constant $\Delta m = 3.85$, was used to produce measurable diffracted images of the brighter stars. In this manner, the effective dynamic range of the plates was greatly increased, allowing bright *Hipparcos*-magnitude stars to be linked to external galaxies on the same plate. In addition to extending the dynamic range, the grating images also provide a means for calibration and correction of each plate's magnitude equation. A more thorough description of the plate material and the various image systems is given by Girard et al. (1998).

The SPM plates were scanned with the Precision Measuring Machine (PMM) at the US Naval Observatory's Flagstaff Station (NOFS; see Monet et al. 2003 for a description of the PMM). The raw pixel data were saved and later analyzed at the US Naval Observatory in Washington (USNO), to obtain centers and photometric indices for all detectable images.

Beginning in 2000, CCD cameras were installed on the double astrograph in order to complete the SPM second-epoch survey. (Photographic plates with the 103 emulsion were no longer being produced.) Two cameras were installed, a 4 K × 4 K PixelVision (PV) camera (15 μm pixels) in the focal plane of the yellow lens, and an Apogee 1 K × 1 K (24 μm pixels) camera behind the blue lens. The blue camera was later replaced by an Apogee Alta 2 K × 2 K (12 μm pixels) CCD camera. Custom Scientific V and B band filters were incorporated into the PV and Apogee systems, respectively. This results in a passband response for each camera system that roughly approximates its first-epoch photographic counterpart. As with the plates, the objective grating was used during CCD exposures. During CCD observations, the grating is oriented such that the dispersion direction is 45° from north and, hence, 45° with respect to the columns and rows of the CCD. This ensures, for bright stars, that the grating images will not be spoiled by column bleeding of the saturated central image. Exposure times were 120 s, reaching the same depth as the first-epoch plates. A twofold spatial overlap of frames based on the PV's 0.93 × 0.93 deg field of view was initiated for all SPM fields lacking second-epoch plate material. Eventually, when it was found that a single CCD exposure was superior to the multiple first-epoch plate material in terms of astrometric precision, the twofold coverage was changed to single coverage with the PV frames. The yellow lens's PV data were used for both astrometry and photometry. The blue lens's Apogee data were used only in the photometric reductions.

4. SPM4 CONSTRUCTION

4.1. Input Catalog

The astrometric reductions, of both the photographic and CCD data, made use of an input "master" catalog that was necessary to properly identify the various multiple images, i.e., diffraction grating orders and, in the case of the plates, multiple exposures. This master catalog was constructed by combining the following external catalogs in the specified order:

1 = *Hipparcos* (Perryman & ESA 1997)

2 = *Tycho*2 (Høg et al. 2000)

3 = UCAC2 (Zacharias et al. 2004)

4 = Two Micron All Sky Survey (2MASS) psc (Skrutskie et al. 2006)

5 = 2MASS xsc (Skrutskie et al. 2006, largely (but not entirely) galaxies)

6 = LEDA (confirmed galaxies, Paturel et al. 2005)

7 = QSO (Véron-Cetty & Véron 2006)

Objects appearing in multiple catalogs were found by positional coincidence and reconciled by adopting the position of the higher ranked source (*Hipparcos* being considered best). This master input catalog was then used to identify all measurable images within the list of detections in the SPM plate and CCD data. Thus, an object that does not appear in any of these input catalogs cannot appear in the SPM4 catalog. The completeness of the SPM4 is the product of the completeness of these input catalogs and the magnitude limits and resolving limits (i.e., ability to center crowded/blended images) of the SPM material.

There are 670 SPM field centers at declination -20° and southward. The SPM4 is composed of 660 of these fields. There are nine -20° fields for which first-epoch plates were never taken and one -20° field for which the first-epoch plates were mistakenly not measured. Thus, the northern boundary of the SPM4 sky coverage contains a small number of "notches" at which the northernmost stars are at approximately -21.9° instead of -20°.

An input master catalog, as described above, was constructed from cutouts of the external source catalogs for each of the 660 SPM fields included in the SPM4. Within a single field, each object was assigned a "master" ID number that was simply the running number corresponding to the order of that object in the field's cumulative list. Thus, *Hipparcos* stars would be assigned the lowest numbers, increasing through *Tycho2* stars, UCAC2 stars, etc. Combining the three-digit field number with the seven-digit master catalog number within a field yields a star's overall SPM4 ID number. Since many stars in the substantial overlap of neighboring fields would possess multiple IDs, the ID from the lowest-numbered field was adopted as the unique SPM4 identifier.

4.2. Astrometric Reduction

All SPM plates were scanned with the PMM at NOFS. The raw pixel data from the scans were stored and sent to USNO for analysis. The existing StarScan pipeline (Zacharias et al. 2008) was heavily modified by USNO staff to accommodate the SPM pixel data. The overall process included a conversion of the PMM transmission values into density values, smoothing the data for the purposes of image detection and background fitting, and then fitting the unsmoothed two-dimensional (2D) density profiles with an azimuthally symmetric exponential function. (Tests using an elliptical exponential function showed no improvement over the azimuthally symmetric function, even for the slightly elongated first- and second-order diffraction images.) The derived image positions on each of the 884 PMM CCD footprints required to cover an SPM plate were then transformed into a single global coordinate system using information from the overlapping regions of adjacent footprints and the laser interferometric metrology of the footprint centers. As the resulting astrometry from all first-epoch SPM plates was included in the construction of the UCAC3 catalog, further discussion of the PMM data analysis can be found in Zacharias et al. (2010). The USNO-derived centers and image parameters for all detections on the SPM plates (both first- and second-epoch plates) were then provided to the Yale SPM team for subsequent reduction.

The SPM CCD frames are corrected for bias, dark (in the case of the Apogee frames; dark current is negligible in the PV), and flatfielding. SExtractor (Bertin & Arnouts 1996) is used to identify detections, give aperture photometry, and provide preliminary (x, y) centers. Final (x, y) centers are derived by fitting 2D elliptical Gaussian functions to the image intensities. See Casetti-Dinescu et al. (2007) for further details of the astrometric reduction procedures used with the PixelVision camera data.

In general, techniques similar to those used in constructing previous versions of SPM catalogs were used to build the SPM4 (see Girard et al. 1998, 2004; Platais et al. 1998a). Stars for which both the central-order exposure and first-order grating-image pair are measurable were used to derive and correct each plate's magnitude equation individually. Following the procedures developed for the SPM1 and SPM2 catalogs, all extended sources were given magnitude corrections corresponding to their measured magnitude shifted by -0.7, an empirically determined correction that compensates for the difference between a plate's star-image and galaxy-image magnitude equations.

In the case of the CCD image centers, there were systematic offsets detected between the position of the central image and the mean of the positions of the grating-order pairs. However, these did not follow the behavior expected for magnitude equation or charge transfer efficiency effects. Therefore, this offset was corrected as such, a simple offset between the image order systems, instead of as a magnitude equation (see Casetti-Dinescu et al. 2007).

Measures from all exposures and all grating-image systems were transformed to a single system for each plate and each CCD frame. The CCD (x, y) positions from the PV frames were also corrected for a fixed-pattern geometric distortion believed to be associated with the filter. Figure 2 shows the distortion pattern. The correction "mask" was built up from residuals of hundreds of frames, at different pointings, reduced into UCAC2 coordinates. The corrected CCD (x, y) positions were then transformed onto the system of the UCAC2 to facilitate pasting together the roughly 50–100 frames (depending on whether it had twofold or single coverage) that comprise a 6 deg $\times$ 6 deg SPM field. An overlap method is employed to perform this task, using *Tycho2* stars as an external reference system to ensure that systematics from the individual overlap solutions do not accumulate. In this manner, an artificial "pseudo-plate" is built up from CCD frames. This pseudo-plate can then be treated the same as a real second-epoch plate.

In previous versions of SPM catalogs, first- and second-epoch plate pairs were combined to yield relative proper motions per plate pair. These were then corrected to absolute proper motions using external galaxies in the case of SPM1 and SPM2, or *Hipparcos* star proper motions in the case of SPM3. For the SPM4, instead of combining plate pairs, we have decided to construct the best possible position catalogs at first and second epochs, over the entire coverage area. This is accomplished by dividing the plates into three groups—first-epoch plates, second-epoch plates, and second-epoch pseudo-plates—and combining

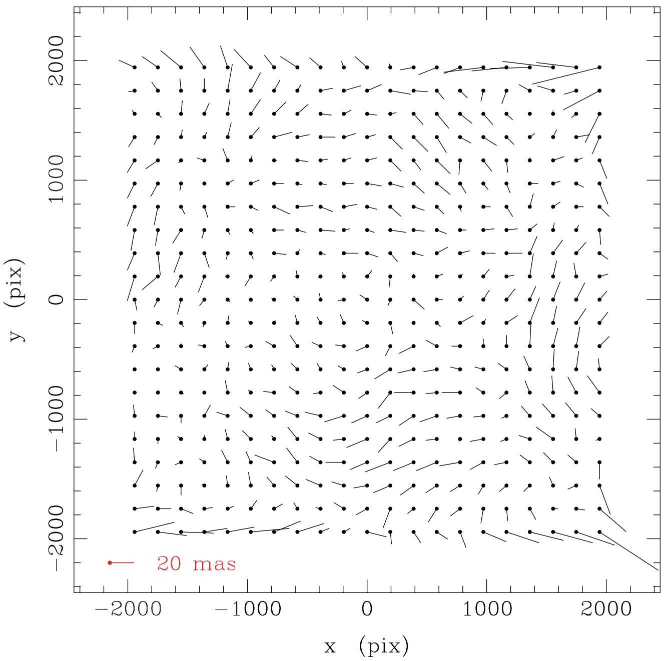

Figure 2. Field-distortion correction mask for the PV CCD/filter combination. The mask was derived by stacking residuals of PV frames reduced into UCAC2 positions. The scale of the vectors is as indicated in the lower left.

(A color version of this figure is available in the online journal.)

positional data within each group using a plate-overlap strategy as follows.

Within each of the plate groups, all plates are pushed through the software pipeline that performs the preliminary reductions described above. This pipeline combines multiple images of the same star (short/long exposure and diffraction orders), corrects the positions for magnitude equation, and then models these (x, y) positions into (α, δ) from a subset of the *Tycho*2 catalog adjusted to the epoch of the plate. (The subset is roughly half the *Tycho2* stars, those of better quality.) The plate model consists of classical fifth-order distortion terms plus a general third-order polynomial. Uncertainties as a function of magnitude are derived from the scatter in position of stars with multiple images.

With each plate having been reduced into (α, δ) on the system of *Tycho2*, stars in the overlapping areas are used to make further adjustments to each plate's model. This is done in an iterative approach as opposed to a simultaneous global solution. The procedure used consists of the following steps.

1. For each plate within the plate group, identify all stars on the plate that also have measures on other, overlapping plates.
2. Create an "internal" reference catalog from a weighted average of these overlapping stars's (α, δ) values, obtained from the previous iteration, for the entire plate group. Weights are derived from the individual positional uncertainty estimates.
3. Create an "external" reference catalog from the source catalog positions of *Hipparcos* and *Tycho2* stars present on the plate, adjusted for epoch using the source catalog proper motions. External catalog positions supersede internal ones.
4. Model the plate into the combined "internal plus external" reference catalog using a general third-order model plus classical fifth-order distortion, retaining these high-order terms only when they are significant.
5. Only after all plates have been modeled, apply the updated model coefficients, calculating new (α, δ) per object and per plate.
6. Construct an updated positional catalog of all objects on all plates in the group. Use the weighted average position of multiply measured objects, yielding a catalog with a single position per object.
7. Examine the differences in positions, comparing the newly constructed catalog with the previous iteration's version. If the differences are significant, go back to step 1 and begin a new iteration.

The presence of the *Hipparcos*/*Tycho2* stars in the reference catalog prevents errors from the overlap solutions from accumulating and causing a reference system drift. The number of iterations required for convergence was from five to nine for the three plate groups. When all is done, i.e., after sufficient convergence of the iterative solutions, the weighted-average positions for every object on every plate are derived and adopted as the celestial coordinates of that object, at the weighted mean epoch for that particular star.

This procedure was applied to the first-epoch plates, the second-epoch plates, and the second-epoch pseudo-plates that had been pasted together from the PV CCD frame data. For this last group, a second pasting of the CCDs was performed using preliminary proper motions derived from a first iteration to update all CCD data within a single pseudo-plate to the same epoch. Also, for the pseudo-plate regions it was realized that there were some holes in the sky coverage due to several causes. In areas with single-fold coverage, inaccurate telescope pointing led to occasional gaps between adjacent PV frames. Additionally, some frames that had passed a quality check at the telescope were later found to have problems that rendered them unusable. Finally, there were a handful of SPM fields for which the second-epoch plates were unusable and pseudo-plates had to be created from an incomplete number of CCD frames in these fields. In order to avoid having holes or cracks in the SPM4 sky coverage for want of second-epoch positions in these cases, it was decided to supplement the pseudo-plate fields with second-epoch positions taken from the master input catalog. The additional stars and galaxies added were those with input catalog V estimates less than 17.5, in general, but a cutoff of $V = 16.5$ was used in two Galactic plane fields. Of course, in order to appear in the final SPM4 catalog, a corresponding detection and measure of the object in the first-epoch plate material must exist. Objects with proper motions derived in this manner can be identified in the catalog; their values of np and nc, the number of second-epoch plate and CCD measures per object, will both be zero.

Upon completion, first-epoch positions and second-epoch positions on the system of the ICRS had been obtained for all detected objects in the 660 fields. Uncertainties in the positions were derived from the scatter of multiply measured stars as a function of magnitude and this empirical relation was then adopted for all objects, whether multiply measured or not. The positions and uncertainties were then combined to yield proper motions and proper-motion uncertainties in a straightforward manner. While in theory these proper motions should be on the system of the ICRS via *Hipparcos* and *Tycho2*, and thus absolute, in practice an additional correction is needed. Examining the measured proper motions of galaxies within each field as well as the differences with *Hipparcos* proper motions at the bright end, it was apparent that a residual magnitude equation remained in the derived proper motions. The source of this magnitude equation is not certain. The offsets vary with position, in particular being highly correlated with right ascension. Also, the offsets at the faint end, i.e., with respect to galaxies, are much larger than those at the bright, *Hipparcos*-linked end. This suggests that the cause might be a magnitude-dependent systematic in the *Tycho2* reference system used, one that is coherent over large angles in the sky and is, presumably, contained in the *Tycho2* proper motions.

Whatever its cause, it was decided to calculate a final correction to absolute proper motion, per SPM field. The form of the adopted correction is linear with magnitude, being anchored at the mean magnitude of galaxies and that of *Hipparcos* stars and based on the mean proper-motion offsets of those two sets of proper-motion reference objects. Such a linear correction with magnitude was derived for all 660 fields. The size of the corrections was less than $\sim$1 mas yr^{-1} at $V \sim 8.5$ (*Hipparcos* magnitudes) but was typically several mas yr^{-1} at $V \sim 17.5$ (galaxy magnitudes). More precisely, the mean proper-motion zero-point corrections in ($\mu_\alpha \cos(\delta)$, μ_δ) for the 660 SPM fields were (−0.22, +0.24) mas yr^{-1} at the bright end and (−0.36, −1.83) mas yr^{-1} at the faint end, and the standard deviations of the distribution of corrections were (0.41, 0.68) and (0.97, 1.50) mas yr^{-1}. The actual proper-motion correction applied to each star in the catalog was the weighted mean of the corrections for the three closest field centers to the star, weighted by the inverse square of the distance from the field centers.

4.3. Photometric Reduction

The B, V photometry in the SPM4 is extremely heterogeneous. In some cases, it is derived from second-epoch SPM blue and visual filtered CCD frames. In some cases, it is derived from the PMM measures of SPM first-epoch plates. And in the cases where neither of these are available or reliable, it is propagated from the input master catalog. In this latter group, one can find relatively good photometry from *Tycho*2 or less reliable extrapolations to B and V magnitudes from 2MASS (J, H, K). As such, it is difficult to estimate uncertainties for much of the B, V photometry listed. SPM4 magnitude errors are as likely to be caused by spurious radius measures or inappropriate extrapolations as they are by signal-to-noise considerations. Thus, we do not provide individual uncertainty estimates for the B, V photometry listed. We do, however, indicate the source of the B and V values given, be they CCD-based, plate-based, or input catalog values.

For the purpose of identifying which image orders should be expected (and thus searched for) within the list of detections on a plate or CCD, a magnitude estimate of each star in the input master catalog is needed. For *Hipparcos* and *Tycho2* stars, the $B_{\rm Tycho}$ and $V_{\rm Tycho}$ values (corrected to the Johnson system) served this purpose. For almost all other stars, B and V photometry was not available so an approximate extrapolation was derived based on 2MASS (J, H, K). *Hipparcos* and *Tycho2* stars, which have both B, V and 2MASS photometry, were used to calibrate each SPM field with a relation of the following form, suggested by the work of Bilir et al. (2008):

$$B-J = b_0+b_1(J-H)+b_2(H-K)+b_3J(J-H)+b_4J(H-K), \quad (1)$$

with a similar function for $V-J$. These were used to provide an approximate estimate of B and V for stars without *Tycho2* photometry. For the small fraction of objects without either *Tycho2* or 2MASS photometry, the objects were assumed to be faint and arbitrarily assigned the magnitude limit of the plate or CCD on which it was expected to fall. Again, these input master catalog B, V magnitude estimates were primarily to aid in identifying the various image orders detected. Only in the case that there was neither SPM plate-based photometry nor SPM CCD-based photometry did these estimates find their way into the final catalog.

The PV and Apogee/Alta CCD frames of the second-epoch SPM survey were reduced in typical fashion using aperture photometry with calibration into *Tycho2* V and B photometry (corrected to the Johnson system). When available, these CCD-based magnitudes are provided in the SPM4 catalog, superseding any other magnitude estimates. As the PV camera's field of view is larger than that of the Apogee/Alta cameras, a substantial number of stars have CCD-based V magnitude estimates and photographic B estimates.

Photographic photometry based on the parameters of the image model fits of the PMM scan data proved to be problematic. Among the various image model fit parameters derived, the fit radius provided the best (although still poor) correlation with external calibrating photometry. Calibration was into *Tycho2* V and B photometry, supplemented with stars from the Guide Star Photometric Catalog (Lasker et al. 1988). The form of the calibration was that of a cubic polynomial in the image radius. For extended sources, the radius was inappropriate. For such objects the input master catalog's magnitude estimate was retained instead, unless there existed CCD-based photometry. Also, there was a large, non-Gaussian scatter between the radius measures and calibrating photometry, indicating that at times the radius estimate was simply erroneous. Thus, during the SPM4 plate photometric reduction procedure, a comparison was made between the preliminarily derived (radius-based) magnitude and that from the input master catalog. If these differed by more than one magnitude, it was interpreted as evidence that one or the other was in error. Since we could not know which, a somewhat expedient choice was made; the fainter of the two magnitude values was retained, under the assumption that the steepness of the luminosity function implies that it is more likely that the star is faint. Unfortunately, the only relevant flag that was retained per star was whether or not it had passed through the plate photometry portion of the pipeline, not whether the resulting magnitude estimate was truly plate-based or a retention of the input master catalog value. The photographic photometry was disappointingly poor in any event. Thus, the only truly reliable B, V photometry in the SPM4 catalog is that flagged as being CCD-based, i.e., with ib = 3 and/or iv = 3.

4.4. Compilation and Content

The final astrometry and photometry were combined with other relevant metrics from the reduction pipeline to construct the SPM4 catalog. The other quantities listed in the main catalog include: uncertainty estimates for the astrometry; mean epochs of observation; the numbers of observations at each epoch; an SPM4 identifier; and flags identifying the input source catalog, source of the photometry, and whether or not the entry is matched to an extended source or extragalactic object. Additionally, for convenience, J, H, K photometry from the 2MASS catalog is included for all objects with a 2MASS counterpart. Table 1 describes the contents of a single record of the main catalog, detailing its structure and format.

The astrometric reduction procedures described earlier included checks for spurious measures. Typically, more than one image of an object was available to use and, thus, eliminating a single image did not generally mean the elimination of a star.

Table 1
SPM4 Contents

Column	Bytes	Format	Name	Unit	Description
1	001–012	f12.7	ra	deg	Right ascension (ICRS, epoch = 2000.0)
2	013–024	f12.7	dec	deg	Declination (ICRS, epoch = 2000.0)
3	025–030	f6.1	era	mas	Uncertainty in right ascension
4	031–036	f6.1	edec	mas	Uncertainty in declination
5	037–045	f9.2	pma	mas yr^{-1}	Absolute proper motion in ra ($\mu_\alpha \cos\delta$)
6	046–054	f9.2	pmd	mas yr^{-1}	Absolute proper motion in dec
7	055–061	f7.2	epma	mas yr^{-1}	Uncertainty in pma
8	062–068	f7.2	epmd	mas yr^{-1}	Uncertainty in pmd
9	069–074	f6.2	B	mag	*B* magnitude
10	075–080	f6.2	V	mag	*V* magnitude
11	081–083	i2,i1	ib,iv		Source flags for *B* and *V* magnitudes
12	084–089	f6.2	epav	yr	Weighted mean epoch of observation minus 1950
13	090–095	f6.2	ep1	yr	Weighted mean 1st epoch minus 1950
14	096–101	f6.2	ep2	yr	Weighted mean 2nd epoch minus 1950
15	102–104	i3	mp		Number of 1st-epoch plates used
16	105–106	i2	np		Number of 2nd-epoch plates used
17	107–108	i2	nc		Number of 2nd-epoch CCD frames used
18	109–119	i11.10	spmid		spm4 identifier = field no. + input catalog line
19	120–121	i2	igal		Galaxy/extended-object flag
20	122–122	i1	icat		Input catalog source flag
21	123–129	f7.3	J		2MASS *J* magnitude
22	130–136	f7.3	H		2MASS *H* magnitude
23	137–143	f7.3	K		2MASS *K* magnitude

Notes. Additional notes by column. 3, 4: positional errors are given at the mean epoch of observation, i.e., column 13. 11: if ib/iv is (1; 2; 3), B/V is from (input catalog; first-epoch plates; second-epoch CCD). 14: preliminary proper motions were used to put all CCD "pseudo-plates" at epoch 2007.0. 17: if the number of frames is greater than 9, nc is set to 9. 18: the first three digits indicate the SPM field number. The final seven digits are the running number from that field's input master list, a concatenation of the input catalogs. 19: if 0, there is no indication the object is non-stellar. If (1; 2; 3), then (2MASS extended source; LEDA galaxy; Véron-Cetty & Véron QSO). 20: if (1; 2; 3), the object is from (*Hipparcos*; *Tycho*2; UCAC2). If 4, the object is from the 2MASS point source catalog (psc). If 5, the object is from the 2MASS extended source catalog (xsc). If 6, the object is from the LEDA galaxy catalog. If 7, the object is from the Véron-Cetty & Véron QSO catalog. For objects in multiple catalogs, the first (lowest numbered) catalog source is given. 21–23: J, H, K from 2MASS (psc) for matched objects, otherwise = 0.0.

This applies within each of the single-epoch positional catalogs that were generated in the process of building the SPM4. However, there was no such automatic check during the subsequent construction of the proper-motion catalog. That is, there was no post-construction filtering of the measured proper motion. Thus, there are undoubtedly spurious absolute proper motions in the SPM4. The user is cautioned that the catalog is best suited for statistical studies of samples of stars, rather than searching for individual proper-motion outliers within a population. The catalog is still worthwhile for this latter purpose, but the user is advised to verify unusual individual proper motions with other sources, if at all possible. Somewhat related, it should also be noted that the first-epoch positional catalog generated from the SPM material was used as an early-epoch catalog in the construction of the UCAC3 catalog (Zacharias et al. 2010). Thus, it is possible that some spurious proper motions might be common to these two catalogs.

5. CATALOG PROPERTIES

The SPM4 contains 103,319,647 stars, galaxies, and QSOs. Table 2 breaks this number down by type of second-epoch material, source of *B* and *V* photometry, and intersection with a handful of relevant external catalogs. The spatial distribution of the catalog is shown in Figure 3 as an Aitoff projection of (α, δ). Each dot represents a randomly selected one of every 500 catalog objects. Background shading indicates the total extent of the first-epoch SPM plates. The SPM4 has a northern boundary at $\delta = -20^\circ$, with a small number of notches caused by the lack of first-epoch plates. Low-density patches near the Galactic plane are primarily due to dust and its associated extinction, but there are also areas in which image crowdedness has spoiled the object detection and identification algorithms. Caution should be exercised when using the catalog in such areas.

Table 2
SPM4 Statistics

Total number of SPM4 objects	103,319,647
Objects with second-epoch astrometry...	
from CCD measures	65,355,419
from plate measures	27,042,797
from source-catalog positions	10,921,431
Objects with *B* photometry...	
from second-epoch CCD frames	8,338,220
from first-epoch plates	83,295,995
from source-catalog photometry	11,685,432
Objects with *V* photometry...	
from second-epoch CCD frames	65,262,893
from first-epoch plates	37,624,399
from source-catalog photometry	432,355
Objects in common with...	
Hipparcos	43,889
SPM2	301,624
2MASS extended-source catalog	214,279
LEDA galaxies catalog	85,519
V-C&V quasar catalog	1341
Objects *without* a 2MASS cross-ID	153,192

The magnitude distribution of the SPM4 is shown in Figure 4, based on the same randomly selected subset of the catalog displayed in Figure 3. An artificial bump at bright *V* values (dotted curve) is due to a small fraction of faint stars that suffer simultaneously from having anomalous 2MASS colors (affecting the

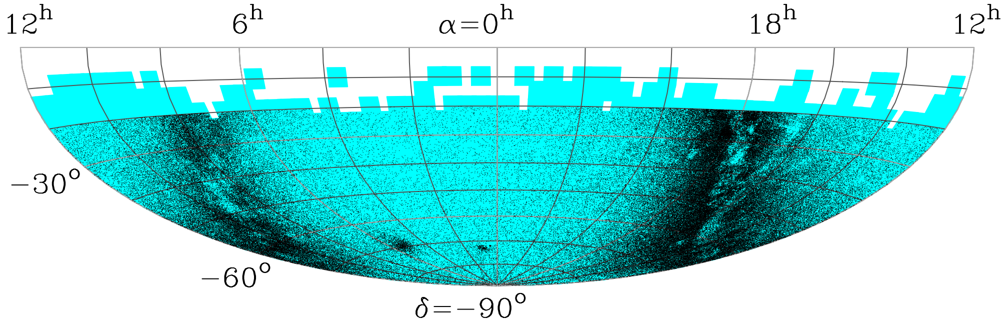

Figure 3. Spatial distribution of the SPM4 catalog. Each dot represents one in 500 objects, randomly selected from the catalog. The background shading shows the total extent of the first-epoch SPM photographic survey. The northern edge of the SPM4 catalog is $\delta = -20°$, minus a handful of slight indentations where first-epoch plates are absent.

(A color version of this figure is available in the online journal.)

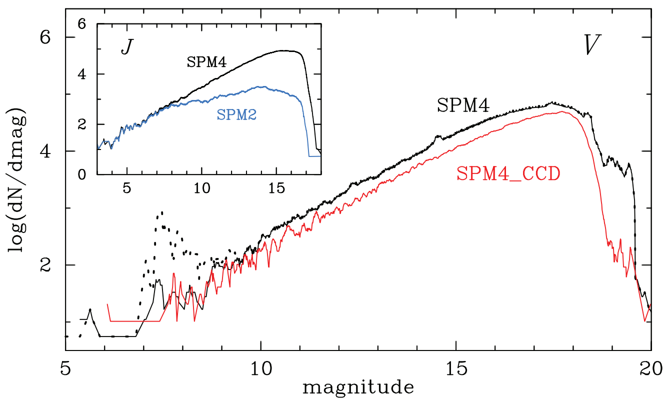

Figure 4. Magnitude distribution of the SPM4. The main panel shows the V distribution of a randomly selected 0.2% of the catalog, consisting of both photographic and CCD photometry. The dotted curve shows the distribution without any cleaning of spurious V estimates. The solid curve is the result after discarding stars with unrealistic $V-J$ values. The red curve shows the distribution of those objects in the subsample whose V magnitude is CCD-based. The logarithmic distribution turns over at $V \sim 17.5$. The inset shows a comparison of the magnitude distributions of the SPM4 and PDS-based SPM2 catalogs. All catalog objects within a specific mid-latitude region, 200 deg^2 in area, are included and the distributions are constructed as a function of 2MASS J so as to avoid spurious features in the SPM4 V photographic photometry.

(A color version of this figure is available in the online journal.)

source catalog V extrapolation) *and* wildly miscalculated SPM photographic photometry indices, including a likely misidentification of the image's exposure system. This feature is a direct result of the inadequacies in the photographic photometry that were discussed in Section 4.3. Fortunately, by filtering out objects with unrealistic $(V-J)$ values, these spurious stars can be expunged, resulting in the solid black curve shown in Figure 4. Alternatively, the catalog's true V distribution can be derived from that portion of the SPM4 with second-epoch CCD photometry, as the CCD-based V estimates are immune from the effect. The red curve in Figure 4 shows only the CCD-based portion of the sample. These logarithmic curves turn over at approximately $V = 17.5$ and this can be considered the completeness limit of the catalog. Note that the faint end of the SPM4 is determined by the 2MASS portion of the input catalog. As such, blue stars near the limit of $V = 17.5$ may not be present in the near-infrared 2MASS catalog and, thus, will not be included in the SPM4 even though these stars would be measurable in the SPM material.

The SPM4's single-coordinate positional uncertainty at mean epoch is plotted as a function of magnitude in the top panel

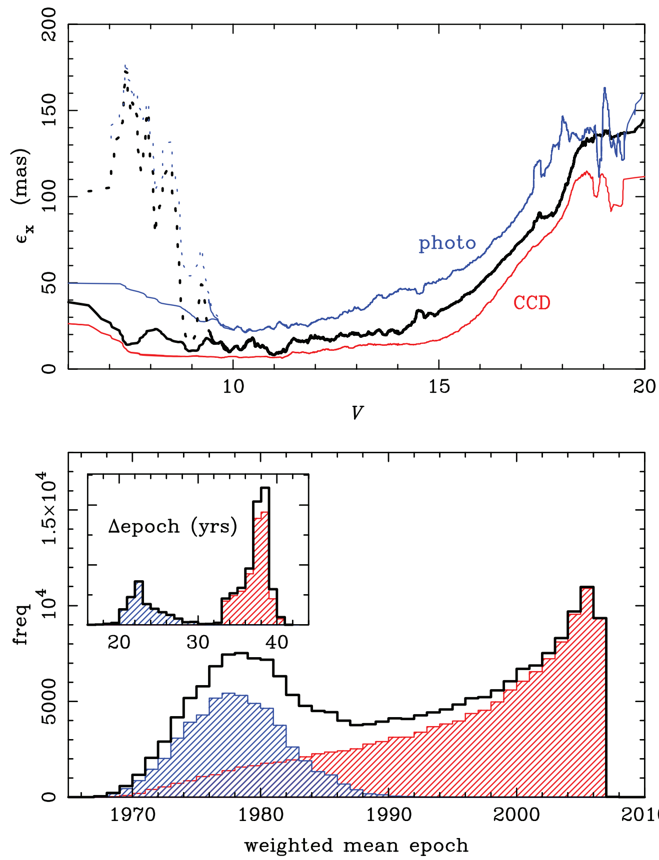

Figure 5. Single-coordinate positional uncertainties at mean epoch as a function of V magnitude. The top panel shows the median uncertainty for the catalog as a whole (black curves), for that portion with second-epoch photography (blue curves), and for that portion with second-epoch CCD astrometry (red curve). A group of faint stars with incorrect photographic V values accounts for the artificial rise at $V < 10$ (dotted curves). See the text for further explanation. Filtering the sample by $(V-J)$ allows these erroneous stars to be expunged, revealing the true magnitude of the uncertainties at the bright end (solid curves). In the bottom panel, the distribution in weighted mean epoch is shown (black curve) along with the distributions of objects separated by second-epoch observation type; photographic plates (blue hatching) or CCD (red hatching). The uncertainty-based weighting scheme and superior astrometry of the CCD second-epoch positions skews the distribution toward the CCD era. The inset shows the distribution in epoch difference, using similar color coding.

(A color version of this figure is available in the online journal.)

of Figure 5, based on the one-in-500 subset. Again we see the presence of stars with grossly underestimated V magnitudes in the dotted curves that represent the unfiltered sample. The solid

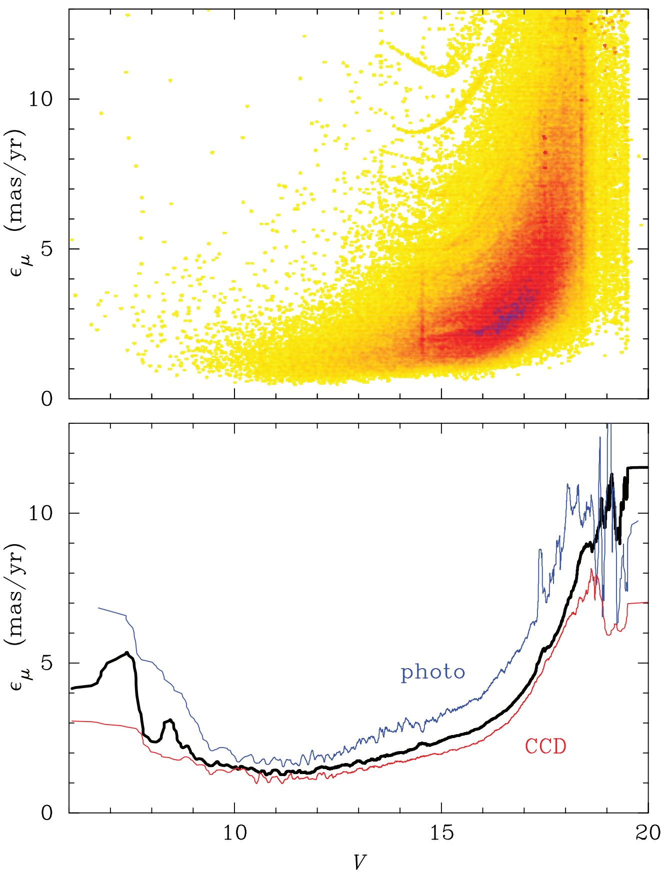

Figure 6. Estimated proper-motion uncertainties as a function of V magnitude. The top panel shows the density of SPM4 objects in the ϵ_μ–V plane, where ϵ_μ is the single-coordinate proper-motion uncertainty. The color coding is linear with density. In the bottom panel, the median relation is shown for the catalog as a whole (black curve). Also shown are the median relations for objects with photographic second-epoch astrometry (blue) and those with CCD second-epoch astrometry (red). The contaminating set of stars with erroneous photographic V estimates brighter than ∼10 have been removed by trimming the sample in $(V - J)$.

(A color version of this figure is available in the online journal.)

curves—black for the overall sample, blue for the photographic portion, and red for the CCD-based portion—are of the sample after $(V - J)$ cleaning and better represent the true run of positional uncertainty with magnitude. The bottom panel shows the distribution in mean epoch for the sample, broken down by second-epoch observation type, i.e., photographic (blue) or CCD (red). The uncertainty-based weighting used to determine the mean epoch accounts for the values close to the epoch extremes, especially for objects whose second epoch is that of a CCD observation. Note that the catalog also lists separately the mean first epoch and mean second epoch of observation for each object. The inset in Figure 5 shows the distribution in epoch difference; a decidedly bimodal distribution, as is to be expected.

The primary emphasis of the SPM program is proper motions. Figure 6 shows the estimated proper-motion uncertainties as a function of magnitude for the SPM4. In the bottom panel, the median relation is indicated for the catalog as a whole (heavy black curve) as well as separately for that portion of the catalog with second-epoch plate material (blue curve) and that with second-epoch CCD measures (red curve). As can be seen, the formal random errors in proper motion are 2 mas yr^{-1} or better over a substantial magnitude range, roughly $9 < V < 14$. Beyond this, the fewer number of images per star and lower signal to noise ratio steadily increase the errors, reaching ∼5 mas yr^{-1} at $V = 16.5$ and $V = 17.5$ for regions with second-epoch plate and CCD measures, respectively.

As a check on the reliability of the SPM4 proper-motion uncertainties, at least for the portion based on second-epoch plates, an object-by-object comparison was made with the SPM2 catalog. The SPM2 covers a declination band from $-25°$ to $-40°$ and is based entirely on photographic plate material measured with the Yale PDS microdensitometer. Relying essentially on the same plate material, the SPM2 and SPM4 are not independent. However, the difference in measuring machines and centering algorithms used, as well as significant differences in the processing procedures, should result in individual proper motions with largely independent realizations of random errors. As for the reliability of the SPM2 proper-motion uncertainties, they were derived in a straightforward, empirical manner, by comparing proper motions calculated from separate blue- and yellow-plate pairs.

Approximately 300,000 stars and galaxies are in common between the SPM2 and SPM4. The intersection is not complete to any specific magnitude because of the selection criteria used to construct the SPM2 (see Figure 4), but it does sample the entire magnitude range of SPM4, with roughly half of the sample being brighter than $V = 15$. For the purpose of this analysis, the sample was divided, by right ascension, into 30 subsamples of roughly 10,000 objects each. Within each subsample, simple proper-motion differences between SPM2 and SPM4 were normalized by their expected amplitude based on the quadrature sum of uncertainties from the two catalogs. Each distribution of tentatively normalized differences was then analyzed using the probability plot method of Hamaker (1978) to see if it was indeed normal. The inner 98% of each subsample was used in the probability plot analysis, i.e., an outlier frequency of just 2% was assumed. The results are shown in Figure 7. Each point shows the measured Gaussian width for a subsample's "normalized" distribution of proper-motion errors, δ versus α components. A dispersion of 1 would indicate properly calibrated uncertainty estimates. The average value of the subsamples' measured dispersion was 0.95 and 0.97, in the two components. This implies that the estimated uncertainties are well-calibrated, to within a few percent.

Evaluating the systematic accuracy of the SPM4 proper motions is more challenging. Recall that a final zero-point correction was applied, one that was linear with magnitude and tied to *Hipparcos* proper motions on the bright end and external galaxies and QSOs on the faint. Therefore, direct comparisons at this stage to either *Hipparcos* proper motions or to extragalactic sources would not be meaningful. Other possible proper-motion catalogs that might be considered for comparison are the UCAC2 and *Tycho2*. The accuracy of the UCAC2 is similar to its precision, on the order of a few mas yr^{-1}, and therefore would not be useful for this purpose. A comparison to *Tycho2* would only reflect the systematics found in the preliminary SPM4 proper motions discussed in Section 4.2 and attributed to magnitude effects in the *Tycho2* proper motions that had been utilized in setting the reference system for our first-epoch positions. Comparison with deeper proper-motion surveys, for instance those based on first-epoch astrometry from the USNO-A2 or USNO-B1 catalogs or other Schmidt survey catalogs, would also be fruitless, as will be illustrated by an example presented in Section 7.

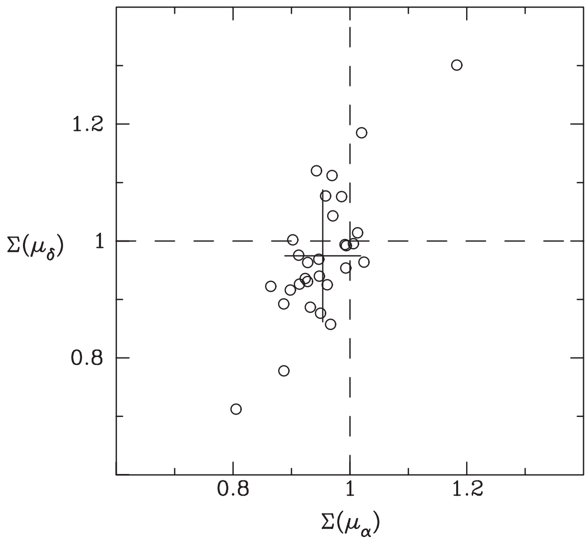

Figure 7. Evaluation of SPM4 proper-motion uncertainty estimates by comparison to SPM2. Each point represents ∼10,000 objects in common between the two catalogs, binned by right ascension. Proper-motion differences, SPM4–SPM2, within each subsample are scaled by the expected amplitude of deviation, i.e., the quadrature sum of the uncertainty estimates from the two catalogs. The distributions of scaled differences within each bin are then analyzed using the probability plot method. The distributions' measured Gaussian dispersions, along μ_α and μ_δ, are plotted for the 30 subsamples. The cross indicates the mean value of (0.95, 0.97), which can be compared to the expected value of (1.00, 1.00) for perfectly calibrated uncertainties.

Instead, we require systems of stars (in order to decrease the random errors) with previously determined absolute proper motions. We have chosen five globular clusters with well-determined absolute proper motions and now redetermine their proper motions from SPM4 for comparison. Table 3 lists the five clusters examined. Reference values of absolute proper motion and their associated uncertainties are taken from the literature. For each cluster, stars are selected from the SPM4 catalog by manually trimming position, proper-motion, and color–magnitude space. The numbers of SPM4 stars per cluster varied from a few hundred to just over a thousand. The mean motion of each cluster was determined, as was the contribution to the uncertainty of the mean from random catalog errors (listed in parentheses in Table 3). Differences between the SPM4 determinations and the literature values were then scaled by the expected amplitude of deviation, i.e., the quadrature sum of the literature uncertainty, the contribution from the SPM4 random errors, and an SPM4 systematic contribution to be solved for. For this rather small sample of five test objects, an SPM4 systematic uncertainty of 1.7 mas yr^{-1} is needed to make the distribution of scaled differences normal. This is larger than the anticipated accuracy of 1 mas yr^{-1} expected from our previous experience with PMM measures of SPM material. We suspect the crowded images within clusters do not lend themselves well to the survey-mode pipelining necessary to build the SPM4. Another possibility is that the linear magnitude correction applied near the end of the SPM4 reductions may, in some fields, be harmful. For instance, if we use the *Hipparcos* stars in the neighborhood of our test clusters to make a constant correction to the SPM4-determined absolute motions, the systematic uncertainty required to normalize the distribution of scaled proper-motion differences drops from 1.7 mas yr^{-1} to 1.3 mas yr^{-1}.

Finally, as discussed in Section 4.3, the (B, V) photometry listed in the SPM4 catalog is extremely heterogeneous, being a mixture of CCD photometry, photographic photometry based on the PMM-measured image radii, and extrapolations of 2MASS (J, H, K). The photographic photometry suffers not only from Gaussian errors associated with the plate scanning and image fitting process but there is also a subset of images with wildly erroneous magnitude estimates, estimates that may be off by five magnitudes or more. These are due to misidentification of image systems and/or inappropriate extrapolations for stars with poorly measured 2MASS colors. Thus, while the catalog does not list photometric uncertainty estimates, flags are included that give the source of the (B, V) data. Only the CCD photometry should be trusted. The precision of the CCD-based V data is ∼0.02 mag for $V < 15$, rising sharply to ∼0.09 mag at $V = 18$. The blue camera produces inferior images but the exposures go deeper. The result is CCD-based B uncertainties that are ∼0.03 for stars brighter than $B = 14$, rising slowly to ∼0.05 at $B = 19$. Conversely, the standard deviation of the photographic photometry is estimated to be on the order of 0.5 magnitudes, but the error distribution has a long, non-Gaussian tail toward artificially bright magnitudes. The lack of reliability of the (B, V) photometry was a compelling reason for including 2MASS (J, H, K) photometry in the SPM4.

6. CATALOG VERSIONS

Several previous versions of the SPM catalog have been released and remain available. These should not necessarily be considered superseded by the current SPM4. A brief description

Table 3
Globular Cluster Proper Motions[a]

Cluster:	Reference		SPM4		SPM4 Ref	
NGC...	$\mu_\alpha\cos\delta$	μ_δ	$\mu_\alpha\cos\delta$	μ_δ	$\Delta\mu_\alpha\cos\delta$	$\Delta\mu_\delta$
104	5.83 ± 0.17[b]	−2.59 ± 0.17[b]	7.67 (0.11)	−3.30 (0.10)	1.84	−0.71
3201	5.28 ± 0.32[c]	−0.98 ± 0.33[c]	7.18 (0.10)	−3.39 (0.10)	1.90	2.41
5139	−5.08 ± 0.35[d]	−3.57 ± 0.34[d]	−3.58 (0.13)	−4.49 (0.15)	1.50	−0.92
6121	−12.76 ± 0.23[e]	−19.38 ± 0.25[e]	−12.70 (0.33)	−17.40 (0.33)	0.06	1.98
6397	3.56 ± 0.04[f]	−17.34 ± 0.04[f]	1.17 (0.06)	−15.65 (0.06)	−2.39	1.69

Notes.
[a] Proper motions expressed in mas yr^{-1}.
[b] Anderson & King 2003 plus Kallivayalil et al. 2006; Freire et al. 2003 (weighted average).
[c] Casetti-Dinescu et al. 2007.
[d] Dinescu et al. 1999.
[e] Dinescu et al. 1999; Bedin et al. 2003; Kalirai et al. 2004 (weighted average).
[f] Milone et al. 2006; Kalirai et al. 2007 (weighted average).

of the major SPM catalog releases and their differences is warranted, as their relative strengths and weaknesses are relevant to the potential user.

The SPM1 is based on Yale PDS measures of plates from 30 SPM fields around the south Galactic pole. It covers $\sim$720 deg^2 and contains 58,887 objects. Two subversions were released, the SPM 1.0 and SPM 1.1, the latter being superior in that it included improvements made to the magnitude-correction scheme.

The SPM2 is also based on PDS measures but covers a larger swath of sky; 156 SPM fields totaling $\sim$3700 deg^2. These are all fields in the -25° to -40° declination bands, but minus the low galactic latitude fields. The SPM2 (the one and only release being the SPM 2.0) contains 321,608 objects. As with the SPM1, the SPM2 is not intended to be complete to any magnitude and, indeed, is far from it. The slow throughput of the PDS microdensitometer precludes measuring all of the images present in the plate material. Thus, an input catalog was adopted, composed of objects of interest gleaned from the literature, utility objects (i.e., images necessary for the reduction procedures), visually confirmed galaxies, and a large number of randomly selected anonymous stars intended for kinematic investigations. The result is a magnitude distribution for the SPM2 that is skewed strongly toward brighter stars. This is illustrated in the inset of Figure 4.

Absolute proper motions in both the SPM1 and SPM2 are referred to as galaxies. Positions are on the system of the ICRS via a subset of Tycho2 stars. The SPM1 and SPM2 should be read with care, as the positions are given at the epoch of the *Tycho*2 catalog, 1991.25. Subsequent versions, SPM3 and SPM4, are presented at the more conventional epoch of 2000.

The SPM3 consists of the same 156 fields comprising the SPM2, but in the case of the SPM3 the plates were scanned using the PMM of the NOFS. Image detections and centers were those of the PMM scanning/measurement pipeline. For convenience, an input catalog was still utilized in transforming these into an SPM 3.0 catalog, but now an attempt was made to have the input catalog be complete to roughly the limit of the SPM plate material. This was accomplished by combining source catalogs consisting of *Hipparcos*, *Tycho*2, UCAC2, and a magnitude-clipped USNO-A2. Shortly thereafter the 2MASS all-sky catalog was released and the USNO-A2 portion of our input catalog was replaced with 2MASS, resulting in version SPM 3.1. Two subsequent improvements (fixes, actually) in the reduction code led to the definitive SPM3 version, SPM 3.3. The SPM 3.3 catalog contains $\sim$11 million stars and galaxies. It differs from the SPM1 and SPM2 catalogs not only in magnitude completeness but also in the absolute proper-motion reference used. The SPM 3.3 proper motions are tied to the ICRS entirely through the use of *Hipparcos* stars.

The current catalog, SPM4, is the first release that combines PMM measures of SPM photographic plates with second-epoch CCD measures. All previous SPM catalogs were based exclusively on photographic material. The SPM4 uses a slightly expanded input catalog source list, compared to that of the SPM3, as described in Section 4. It also differs from previous versions in the manner in which the proper motions are tied to an inertial frame, using Hipparcos stars on the bright end and galaxies and QSOs on the faint end, with a linear interpolation as a function of magnitude. Other important differences with previous SPM catalogs, such as the creation of separate first- and second-epoch positional catalogs during its construction, can be found in the detailed description of Section 4.

Which catalog to choose depends on the intended use. The incomplete SPM2 is based on PDS measures, which are more precise than PMM measures of the same plates. Also, the SPM2 was a small enough project that a significant amount of human interaction could be made during the reduction and evaluation process, on a field-by-field basis. Thus, the SPM2 is less likely to contain individual stars or entire fields that are affected by undetected "blunders." The sheer numbers involved in the SPM3 and SPM4 precluded a high level of human checking of the results. On the other hand, the severe incompleteness of the pre-SPM3 catalogs places limitations on their usefulness. Finally, if a star or set of stars of interest are in both the SPM3 and SPM4, the SPM3 astrometry is likely to be marginally less precise, due to the refinements in centering implemented for the SPM4. However, systematics in the absolute proper motions of the SPM3 are expected to be smaller than those in the SPM4. This is because SPM2 astrometry was used to help calibrate the SPM3, while the SPM4, which extends well beyond the coverage of the SPM2, could not benefit from such a calibration.

7. SUMMARY

We present a comprehensive description of the SPM4 catalog, the latest and largest astrometric product of the Yale/San Juan Southern Proper Motion program. The SPM4 contains positions, absolute proper motions, and B, V photometry for over 100 million stars and galaxies south of -20° declination. Emphasis is on the astrometric aspect of the catalog, particularly the absolute proper motions, which have a precision of $\sim$2 mas yr^{-1} for well-measured stars. The proper motions are on the system of the ICRS and have an estimated systematic accuracy on the order of 1 mas yr^{-1}.

It is worth noting that the SPM4 is based on an astrometric observing program that was intended from its outset to generate absolute proper motions of high precision and accuracy. This sets it apart from recent proper-motion catalogs that rely on photographic Schmidt survey measures for early-epoch positions. The distinction in precision is readily seen by comparing SPM4 proper motions with, for instance, those from the XPM catalog (Fedorov et al. 2010) and the PPMXL catalog (Roeser et al. 2010). Figure 8 shows such a comparison for a 30 arcmin $\times$ 30 arcmin region centered on the globular cluster NGC 6397. The intrinsic proper-motion dispersion of the cluster is negligible and that of the field is relatively low at this Galactic pointing ($l = 338^\circ$, $b = -12^\circ$). Only the SPM4 proper motions show a discernible separation of cluster and field stars.

The SPM4 is well-suited for kinematic studies of the Galaxy, particularly when combined with complementary radial-velocity data. An example of such a 3D study is that of Casetti-Dinescu et al. (2011), in which the SPM4 is merged with the second data release of the RAdial Velocity Experiment survey (RAVE; Zwitter et al. 2008). By isolating red clump stars common to the two surveys, Casetti-Dinescu et al. (2011) are able to derive the properties of the thick-disk velocity ellipsoid, including its dispersions and tilt angles, as well as the vertical gradient of the rotational component. They have also used this sample to deduce an interesting disparity between the currently accepted value for the motion of the local standard of rest based on stars within 1 kpc and the motion observed relative to more distant tracers, beyond 1 kpc. Other intriguing results await further exploitation of the SPM4 data.

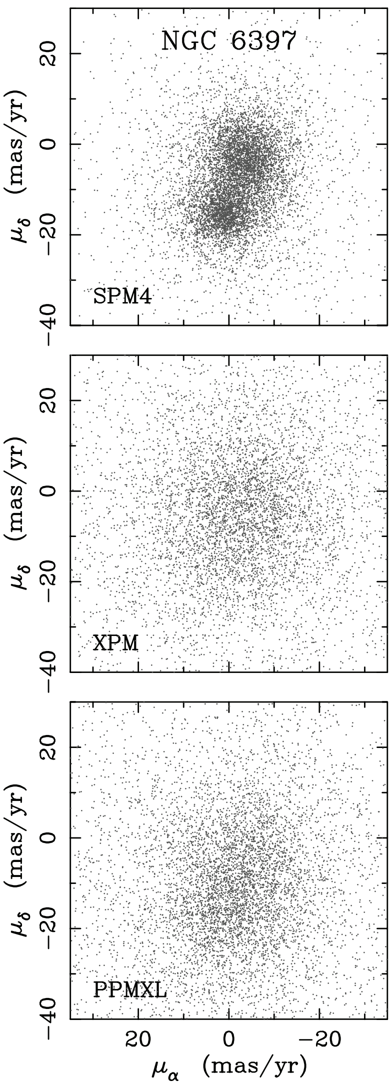

Figure 8. Comparison of SPM4, XPM, and PPMXL catalogs in the field of NGC 6397. The proper-motion vector point diagrams are of all objects within a 30 arcmin × 30 arcmin region centered on the cluster. The top panel shows SPM4 proper motions, the middle panel shows the XPM proper motions, and the bottom panel shows PPMXL proper motions. The field-star and cluster distributions are readily discernible only in the SPM4 data.

The entire SPM4 catalog is available via ftp download[9] or, upon request from the first author, in compressed form on a single DVD disk. We are also in the process of making the SPM4 available via the Web-based VizieR service, facilitating those users who wish to make extractions around areas of interest.

The SPM program is a decades-long endeavor involving the participation of several institutions and countless people. These "countless" many, beyond the authors of this manuscript, have contributed greatly to the success of the SPM program and its culmination with the release of the SPM4 catalog. The following is a modest attempt at listing all those involved: Imants Platais (Johns Hopkins), Vera Kozhurina-Platais (STScI), Reed Meyer (TripAdvisor LLC, Boston), Arnold Klemola (Lick Obs.), René Méndez (Univ. de Chile), Xinjian Guo (Yale), Paulo Holvorcem (Univ. Estadual de Campinas, Brazil), John T. Lee (Interactive Data, Boxborough, Mass.), Zhenghong Tang (Shanghai Astronomical Obs.), Vladimir Korchagin (Federal Southern Univ., Russia), Ting-Gao Yang (Chinese Academy of Sciences, Time Service Center), Wen-Zhang Ma (Beijing Normal Univ.), Chun-lin Lu (Purple Mountain Obs.), Gary Wycoff (USNO), Charlie Finch (USNO), and Jin-Fuw Lee (IBM, deceased).

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9 See www.astro.yale.edu/astrom/.

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