THE YALE-SAN JUAN SOUTHERN PROPER MOTION PROGRAM (SPM)

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ABSTRACT. The Southern Proper Motion Program (SPM) is described and progress in the execution of the second-epoch is outlined, as are the reduction methods. Recent changes in the instrumentation, including the addition of a computer control room to the astrograph building and the construction and operation of a new survey machine are discussed.

1. Introduction

The Southern Proper Motion Program (SPM) is the extension of the Lick Observatory Northern Proper Motion Program (NPM) into the southern hemisphere. The scientific goals of the two projects are very similar and have been discussed extensively in the literature by Vasilevskis (1973), Klemola, *et al.* (1987), and Klemola (1988) for the NPM and by Wesselink (1974) and van Altena, *et al.* (1986,1987) for the SPM. The primary objectives are the determination of absolute proper motions of stars with respect to faint galaxies. Given these absolute proper motions, it is then possible to study the errors in the fundamental system of proper motions, by comparing the FK5 proper motions (or the International Reference System motions) with the absolute proper motions for the same stars. While the absolute proper motions will, no doubt, have systematic errors of their own, they will be different from those of the fundamental motions and should therefore help us to understand and correct the errors in the fundamental system of motions. In addition, the new absolute proper motions will provide an enormous data base for the study of galactic structure and solar motion problems, as done recently with the NPM data by Hanson (1987), and for the determination of statistical and secular parallaxes of various classes of stars too distant for the trigonometric parallax method.

2. Instrumentation

The double astrograph is located at El Leoncito, Argentina in the foothills of the Andes mountains at an elevation of 2400 meters and consists of two f/7 51-cm (20-inch) astrographs with plate scales of 55.1"/mm corrected for the blue and yellow light, respectively, mounted together inside a 1.5 meter fork mounted tube. The passband in the blue is defined by the lens transmission and the sensitivity

J. H. Lieske and V. K. Abalakin (eds.), Inertial Coordinate System on the Sky, 419–426.

of the 17x17 inch 103a-O plate, while the yellow passband is defined by the OG4 (now catalogued as OG515) filter and the 17x17 inch 103a-G plate. The telescope is controlled by an IBM PC computer that sets the telescope on the guide star, while it is guided by an image dissector guider similar to the one used for the Lick astrograph. The IBM PC and all of the control electronics for the telescope are located in a newly constructed control room that connects to the astrograph enclosure. Precision encoders for the right ascension and declination axes have been recently constructed and installed that enable us to accurately set on the guide stars and avoid the time consuming search for the field center in the finder telescope. The computer interfaces, encoders and auxiliary electronics were designed and built by Molina, while the control room was designed by Arq. Maria Rosa Ridl of the Felix Aguilar Observatory and constructed by our workers in residence at El Leoncito.

The limiting magnitude of the astrograph is approximately 19 and 18 on the blue and yellow plates, respectively, with a 4 magnitude objective grating and a two hour exposure. Each plate contains the two hour exposure and a two minute exposure offset from the longer one by approximately two mm. The two hour and two minute exposure durations yield image diameters for the two first-order images of the long exposure that are essentially the same as that for the zero-order grating image on the short exposure. By comparing the average position of the first-order grating images on the long exposure with the zero-order image on the short exposure, we are able to extend the magnitude range of measurable stars from about the 4th magnitude to the 18th magnitude where our reference frame of galaxies is located. We can therefore connect our absolute system of faint star proper motions with respect to galaxies to the bright SRS stars.

It is necessary to survey a plate at low magnification prior to its measurement with the PDS microdensitometer in order to locate and identify the target objects, to evaluate the quality of the images, and to determine appropriate parameters for the PDS scan. The large volume of plate material to be processed in the Southern Proper Motion program has warranted the construction of a high-speed, low resolution measuring machine which may perform as both a wide-field plate surveyor and two-plate blink comparator for 17" x 17" photographic plates. The heart of the survey machine is the Mann measuring engine, which was previously used for the Yale Zone Catalogues. The Mann's precision screw drives have been replaced by high-speed ball screws driven by stepping motors controlled by programmable indexers which produce steps of 2.54 microns and accurate large slews at a speed of 20 mm/sec. A video camera and optical assembly rides on the carriage slung beneath the bridge and provides motion relative to the plate in the x-direction. One photographic plate is mounted below the optical assembly on a carriage table which rides along rails providing motion in the y-direction. The second plate is mounted above the optical assembly on a platform supported by a rigid frame attached to the lower plate's carriage table. An upper plate holder provides rotational and translational fine adjustment for alignment with the lower plate. The optical assembly consists of two plane mirrors to erect the lower plate's image, two objective lenses for adjusting the focus of each plate, a pellicle beam splitter to combine the two plates' images, a fixed collimating lens, a series of three interchangeable camera lenses, and a Panasonic b/w CCD video camera which produces images on a 19" monitor. The operator has a choice of three magnifications which allow fields of view of size 11.5 mm x 8.5 mm, 37 mm x 27 mm, or 93 mm x 66 mm; the three different camera lenses are mounted on pneumatically actuated slides which are controlled from the operator's console.

Movement of the camera and plates is controlled by an IBM PC which is also used to read plate coordinates and to create and manipulate catalogue files of stored object positions. It also provides a means for fast, efficient graphic interaction with the video image by displaying a mouse-controlled electronic crosshair directly onto the video image of the plate. The design and construction of the electronics needed to generate the crosshair are due to Molina. A general purpose survey program has been written by C. López and used to test and calibrate the survey machine. The calibration tests indicate that in high magnification mode a stellar image position can be determined with an accuracy of ±10 microns, (single coordinate standard error), by moving the stellar image until it aligns with the crosshair. The alternate method of determining a position, by moving the crosshair with the mouse until it coincides with the stellar image, is much faster but yields a somewhat lower positional accuracy of ±15 microns in high magnification. C. López is now using the survey machine to determine improved coordinates for all of the southern stars in the variable star catalogue and has obtained an average positional accuracy of 0.″7 in both coordinates, which corresponds to 13 microns on the SPM plates. The services of the Gibbs Instrumentation Lab and the Yale Center for Electronic services have been employed to construct this survey machine under the supervision of Girard and van Altena.

3. Research Programs

3.1 Galactic Structure

There are numerous galactic structure problems that can be studied with the absolute proper motions that we will be determining. The most obvious area of investigation is in the determination of Oort's constants of galactic rotation *A* and *B*, as has recently been done by Hanson (1987) for the NPM. Another area of study is the current controversy over the existence of the thick disk postulated by Gilmore and Reid (1983) in contrast to the two component disk/spheroid model of Bahcall and Soniera (1980). In the following Table we list the fraction with respect to the disk of thick disk and spheroid stars at visual magnitudes 12.25, 16.25, and 18.25 for galactic latitudes 20, 30, 45 and 90 degrees using the "standard normalization" of the thick disk and spheroid, 2.0% and 0.125%, respectively, from Table 2 in Bahcall (1986).

Table. Fraction of Thick Disk and Spheroid stars to the Disk

	V=12.25		V=16.25		V=18.25	
b^{II}	F_{TD}	F_S	F_{TD}	F_S	F_{TD}	F_S
20°	0.12	0.01	0.26	0.03	0.47	0.05
30	0.16	0.02	0.32	0.05	0.65	0.13
45	0.20	0.03	0.43	0.11	0.77	0.30
90	0.22	0.05	0.56	0.22	0.76	0.61

From the table we can see that at the lowest latitude where there are still a reasonable number of galaxies to set our absolute proper motion zero point, namely 20 degrees, thick disk stars amount to 12%, 26% and 47% of the disk stars in the sample at visual magnitudes 12, 16 and 18, respectively; at high latitudes the fraction is even higher. The significance of this is that the solution for Oort's rotation constants *A* and *B* will be biased by the presence of a component that may not have the same rotational component about the galactic center as the disk. In particular, Gilmore and Reid (1983) have suggested that the thick disk lags the disk by about 100 km/sec, while several more recent determinations suggest that the lag may be closer to 30 km/sec, *e.g.* Ratnatunga and Freeman (1989). While the above figures depend on the adopted normalizations, which are still very poorly known, they highlight the point that the derived values of Oort's constants must be interpreted in terms of a galactic model that allows for the presence of some fraction of stars from other components. We will have a distribution of anonymous, randomly picked, stars ranging from the 12th to the 18th magnitudes with absolute proper motions from which we will attempt to determine the rotation constants of the different galactic components. In fact, we should be able to determine the relative fractions and kinematic characteristics of the different components from our absolute proper motions and B,V photometry.

3.2 A New Catalogue of Right Ascensions and Declinations for Faint Stars

Due to the increasing need for a faint reference frame to aid in the determination of the fiber positions in the new fiber optic spectrographs used with some of the large telescopes, we plan to construct a catalogue of faint stars with magnitudes in the range 16 - 18. The requirement is for equatorial positions of the target objects accurate to much better than the fiber size, which is usually ≤ 1". At present, there are two principal problems: first, a reference frame from the SRS or the SAO catalogue has a magnitude limit of approximately 9th mag., while the target objects are often 16 and fainter; and second, the density of reference objects is low, one/deg^2 for the SRS and perhaps six/deg^2 for the SAO. In addition, the SAO is not satisfactory in general since the positional accuracy at the current date is usually rather poor due to the old mean epoch of the positions. An additional source is the Guide Star Selection System Catalogue of the Hubble Space Telescope. Unfortunately, there are problems with the GSSS equatorial coordinates near the plate boundaries where the poorly determined high order plate constants on the Schmidt plates can result in systematic errors in the positions that exceed one arcsecond. This problem is a direct result of the lack of a good dense reference system at faint magnitudes. L. Taff (private communication) is exploring ways to modify the reduction procedures with the GSSSC that may yield significant improvements to the systematic accuracy of the GSSSC.

Two projects are currently underway in the southern hemisphere that will improve the reference system substantially, but unfortunately not extend the magnitude limit to the required level. The CPC2 will provide positions accurate to ±0\".06 down to the 10th magnitude (de Vegt, 1988 and de Vegt, *et al.* 1988), and a new survey by the U.S. Naval Observatory will extend that magnitude limit to approximately 12 -14 (Routly, 1983 and de Vegt, 1988) at an accuracy of ±0\".05. We plan to establish a relatively dense network of equatorial coordinate secondary standards in the southern hemisphere down to the 18th magnitude in the course of the second epoch of the SPM. The density of the stars in the range of 16 - 18 magnitudes would be about 10 - 15/deg^2 with an accuracy of about ±0\".10 (s.e.) at a mean epoch ~ 1980. This density of faint secondary standards with absolute proper motions should then be adequate to provide a reference frame in the fields of view of most large reflectors.

4. Star Selection, Measurements and Reductions

We have been selecting stars from the SIMBAD data base for measurement on the PDS. Since SIMBAD includes virtually every object referenced in the astronomical literature, it is an ideal list of astrophysically and astrometrically interesting objects for which absolute proper motions may be of value. We have therefore adopted SIMBAD as our primary source of objects to be measured in the SPM program. Dr. Daniel Egret of the CDS in Strasbourg kindly sent us listings by BITNET of the SIMBAD objects within specific plate boundaries. Using a program written by T.-g. Yang, we extract the data of interest to us from the listing and produce a file that is easily read by other programs. This object file is then analyzed to obtain statistics on the numbers and types of objects present, it also assigns default PDS scan codes and object type codes, and the file is transformed to Survey Machine coordinates. In addition, we are in the process of acquiring a CD reader to read the GSSS catalogue on compact disks and will use it to automatically select an incremental sample of stars to measure down to the GSSS limit of about 15.

The SIMBAD output (and the GSSS supplement) are then downloaded from the VAX to the IBM PC computer that controls the Survey Machine. The PC control program written by C. López, reads the file and the survey machine moves to the first region on the old-new plate pair and the software and mouse controlled cursor on the television screen moves to the first object. Since SIMBAD contains both accurate and poor coordinates (e.g. contrast the SRS stars with variable stars known to an arcminute or worse!) we must correct the coordinates before they can be scanned on the PDS. In addition, we must delete unmeasurably faint or blended objects and objects with defects such as scratches, and also add numerous objects for the astrometric solutions and for our galactic structure research. Each object is therefore examined on both the old and new blue plate in the blink mode; the positions are updated, and the default codes for the object type, PDS scan type and image quality corrected, if necessary, and the updated record is written to an output file. At this time, supplementary objects are added to the list by visual inspection. These additional objects include: a) 80 stars at around the 12th magnitude that will be used for the "Bridge" solutions which relate the short offset exposure to the long main exposure on each plate; b) about 300 stars around the 16th magnitude that will be used as our proper motion reference frame; c) an additional 500 faint stars in the magnitude range 12 - 18 that will be used for galactic structure studies and also form, along with the stars in item b), the faint secondary reference system of equatorial coordinates that we are planning to establish; and d) about 100 galaxies that will define the zero point of our absolute proper motions. Including the objects in SIMBAD, we expect to have a list of approximately 1200 objects to measure on each of our SPM plates. Once the survey of the blue plates has been completed, the yellow plates are inserted and the output list from the blue plates is examined and unacceptable objects are deleted and the coding revised if necessary for the yellow output list. The final blue and yellow lists are then uploaded from the PC to the VAX and reformatted to the PDS input file structure.

The plates are then scanned on the Yale laser interferometer PDS microdensitometer and reduced to coordinates by the digital image centering routines described by J.-F. Lee and van Altena (1983) and further improved by Girard. The accuracy of the derived PDS x,y coordinates is approximately ±0.3 μm (s.e.) according to J.-F. Lee, *et. al.* (1986), while the intrinsic accuracy of the emulsions is about 1 μm, therefore we are not limited by the measuring machine.

The plate reduction procedures begin with a detailed examination of the image centering error analysis along with the image shape parameters for each image. Images that have poorly determined centers or whose "image shape" deviates significantly from the average star, or galaxy, are deleted from the lists at this point. We have found that this procedure for culling out the bad data greatly improves the solutions and does not bias our results. Our photographic photometry in B and V is obtained from the pseudo-magnitudes produced by the image centering program. While this data is internally quite accurate, there is a problem in relating the pseudo-magnitudes to the photoelectric calibration stars due to the variations in the photometric response over the plate. Our photometry is locally accurate to about 0.10 mag., but regional variations over the plate can create systematic errors of 0.5 mag. We are exploring methods to reduce those systematic errors.

Since all SPM exposures are taken with the objective grating in place, each of the brighter stars consists of the zero-order image flanked by symmetrically located grating images reduced by approximately 4 magnitudes. Due to the design of the grating, and the quality of the lenses, it is sometimes possible to measure the zero-order image and the grating images out to the third order, yielding a total of seven images for each exposure. In most cases however, only the first- or first- and second-order images can be measured, but this still yields two or four images instead of a single image. In order to take advantage of the possible use of the multiple images, the plates are scanned in an orientation such that the scan direction is parallel to the grating dispersion and with a scan length sufficient to encompass all grating images out to the third-order. The loss in time due to the long scan length is only about one and a half times the normal scan time, since most of the time in scanning an image is spent in reversing the carriage at the end of each line. The seven grating images are then split up in the image centering software and a center determined for each image separately. The symmetrically located grating images are then averaged to yield one position for each order, and the orders are averaged to yield one position with a "weight" equal to the number of orders averaged. We also archive the individual order positions for the study of systematic errors between the orders and as a function of the image diameter on the plate.

At this point we correct for the effects of atmospheric refraction and then transform the short exposure to the system of the long exposure using the "Bridge Stars" with magnitudes in the range of 10 to 13. The exact magnitude is unimportant, only that the transformation be made without any loss in accuracy and without the introduction of a systematic error, dependent for example on the brightness of the star. We therefore select stars which have image diameters in the long exposure first-order that are equal to the image diameter of the zero-order short exposure. We choose about two bridge star/deg^2 well distributed over the plate, or about 80 stars, which then introduces a zero-point error into the transformed final proper motions of the bright stars relative to the faint stars of approximately 0.4 mas/yr, which is about ten times smaller than the accuracy of our proper motions.

The determination of the relative proper motions can in principal be done at any magnitude, however since we must use the reflex proper motion of the galaxies to set the zero point of the motions, this should be done at the magnitude of the galaxies to minimize the chance of introducing a magnitude equation into the absolute proper motions. In contrast to the bridge solution, we must compromise here since as we go to fainter magnitudes the distribution and selection of galaxies improves, but the accuracy of measurement decreases rapidly as we approach the plate limit. The compromise magnitude range used by the Lick astronomers is around 15 to 17 and ours is similar. We plan to select about 300 faint reference stars for the proper motion solutions, which will require plate constants up to at least the second order in the coordinates. In addition, the real tangential velocities of the stars introduce a "cosmic dispersion" or noise that requires numerous stars to achieve a reliable average motion. We have adopted 300 faint reference stars, which is more that needed, but it will add to the density of faint stars in our final secondary equatorial coordinate system. We select all measurable galaxies that we can find in the survey process, most of which will not be in SIMBAD. The plate constants derived for the faint stars are then used to compute the relative proper motions for all stars and galaxies, and the average of the latter is used to correct the relative proper motions to absolute. The final step in the reductions is to transform the rectangular coordinates into the system of the SRS and calculate Right Ascensions and Declinations for all of the objects. In general, we find about 40 measurable SRS stars on a plate, with an average unit weight error of 0″.12 in the transformations.

The repetition of the second-epoch SPM plates is being done at a rate that will enable us to maintain a 20 year epoch difference and keep the accuracy of the proper motions uniform over the southern sky. To date, approximately 60 regions have been repeated and we are just now starting the measurements and reductions. As mentioned earlier, the error introduced by the Bridge transformation appears to be about 0.4 mas/yr, which is about one-tenth of the accuracy of our proper motions. The zero-point error in our faint star reference system depends on the cosmic dispersion of the proper motions, which for the first regions at mid galactic latitude is about 1.0 mas/yr, while the accuracy of the relative proper motions at V = 14 is approximately 3 mas/yr. On the other hand, the dominant error is that introduced by the galaxy reflex proper motion, which depends critically on the number of measurable galaxies found in each region. That number can be depressingly small and will limit the zero-point of the absolute proper motions in each region to an accuracy of 1 to 3 mas/yr, depending on the number of galaxies.

5. Acknowledgements

We are indebted to a large number of individuals for their contributions to the SPM project. In particular we would like to acknowledge the observers at El Leoncito, past and present, the staff members of the Universidad Nacional de San Juan for their invaluable help, both financial and moral, the electronic and mechanical instrument shops at both the UNSJ and Yale, and Ting-gao Yang for his contributions to the extraction of data from the SIMBAD data files. Finally, we gratefully acknowledge the financial support of the U.S. National Science Foundation and the UNSJ.

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Discussion

SMITH: Is the error quoted for the SRS at 1989 in fact the error of the Perth 70 catalog at 1989?
VAN ALTENA: Two HST calibration regions at $\delta \approx -60°$ yielded an error of ±0.25 arcsec, while the first of the SPM regions at $\delta = -35°$ gave ±0.38 arcsec for the 1989 error of the SRS.

RÖSER: You showed the plot "Peak density of image" versus "radius of image." How is "radius" defined in this plot?
VAN ALTENA: The radius is the "Gaussian radius" from a bivariate fit to the measured densities.