LARGE FUNDAMENTAL AND GLOBAL TRANSIT CIRCLE CATALOGS

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Abstract. The fundamental system is currently based on the Dynamical Reference Frame as defined by the motions of the Earth and other Solar System objects. The link to this frame has traditionally been made by the observation of these objects and of stars in absolute transit circle programs. The zero points of the link are applied to quasi-absolute catalogs, and these are combined with the absolute catalogs to define the fundamental system. The individual positions and motions of the fundamental stars are then strengthened by incorporating differential catalogs reduced to the fundamental system. The system can be extended to higher densities and fainter magnitudes by further systematic reduction and combination of differential catalogs. The fundamental system itself, however, can only be extended through a planned series of observations resulting in absolute stellar positions over a range of epochs. A new fundamental catalog being compiled at the U.S. Naval Observatory is discussed and compared with the existing standard, the FK5.

1. INTRODUCTION

The two main problems that compilers of star catalogs have always faced are, first, to form an internally consistent set of observed positions referred to standard coordinates at the mean epochs of observation, and, second, to make those positions usable at other epochs without introducing distortions or rotations. These problems have traditionally been solved by referring observations taken at many epochs to a standard frame of reference and then combining the observations to give positions at a central epoch as

E. Høg and P. K. Seidelmann (eds.),
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well as proper motions. These positions and motions can then be used to represent the standard frame at all epochs.

When the standard frame is the Dynamical System, and the stellar positions and motions are linked to it through absolute and quasi-absolute observational catalogs, the result is known as a fundamental catalog.

2. TYPES OF CATALOGS

2.1. ABSOLUTE CATALOGS

Catalogs that have been observed and reduced without dependence on existing catalogs and that include observations of Solar System objects are referred to as absolute. These catalogs have been derived almost exclusively from transit circle observations.

The process of producing an absolute transit circle catalog involves two main components: observations that can be reduced to give a consistent, instrumental frame derived from independently reduced nights of observation, and observations of Solar System objects that can be used to tie the instrumental system to the dynamical one.

In order to meet the first requirements the observational program must be conducted in a way that permits each night's observations to be independently reduced to a frame that is consistent from night to night. This is achieved by accurate calibration of the instrument's mechanical configuration and orientation, independent determinations of the azimuth of the instrument, corrections to refraction based on environmental quantities at the time of observation, and reference to an initial equinox point, usually based on the current fundamental catalog. Some of the mechanical calibrations are made relatively frequently. Quantities such as the departure of the axis from the horizontal plane (level), rotation of the axis in the horizontal plane (azimuth), orientation of the lens (collimation), and direction of the vertical (nadir), need to be made every two to three hours. The bending of the tube (flexure) is regularly measured during the course of the program as well. Other measurements, such as calibration of the circles, errors in the axis pivots, and changes of scale in the micrometer (mechanical or photoelectric) can generally be performed two or three times during a program.

The mechanical calibrations serve to fix the instrument within its own frame of reference as well as motion within that frame during the course of each night's work. The link to the celestial zero points defined by the Earth's rotation and orbital motion requires additional measurements. The mechanical calibration of the azimuth mentioned above is generally made with marks which are point sources of light about 100 meters from the instrument. These can give the axial motion in azimuth but not an absolute calibration. An absolute azimuth must come from observations of circumpolar stars made above and below the pole on the same night. This process fixes both the azimuth of the instrument and the pole to which the observations in declination are referred, the IERS Celestial Reference Pole.

In right ascension the procedure is generally to reduce each night's work using a standard catalog, such as the Fifth Fundamental Catalog (FK5) Parts I and II (Fricke et al. 1988, 1991), to link the observations made each night. At the end of the program the observations are first used to derive individual and systematic corrections to the stars of the standard catalog. The tie to the Dynamical System comes from an adjustment of the equinox and equator of the catalog based on the observations made of the Solar System objects and a standard ephemeris, currently DE200 (Standish 1990). This process is much more difficult in practice than in principle. The main problem is that the observations of the stars are made at night, while the Solar System objects that carry the highest weight in the solution, the Sun, Mercury, and Venus, can only be observed during the day. The brightest stars are observed to link the day and night observations, but historically this has been the weakest part of forming an absolute catalog. Observations of the minor planets can help the situation considerably since they are observed at night, but until now they have not been included in the standard ephemerides.

Currently the accuracy that can be achieved for the various calibrations and adjustments of a night's observations on the Washington 6-Inch Transit Circle is in the 20 to 80 mas range. The quantities that are the least reliable are the day-night differences, the flexure, and the refraction. Solution for the refraction has been shown (Høg and Fabricius 1988) to be affected by the presence of internal refraction (INR) in many instruments. INR is also being investigated at the USNO as a possible source of systematic error in the observations of the Sun relative to those of the day stars. In addition, individual nights' observations can suffer from offsets due to heat islands and other sources of anomalous refraction (Hughes and Kodres 1991) With the exception of the day-night differences, improved values for these quantities can be determined at the end of the program through combined solutions.

2.2. QUASI-ABSOLUTE CATALOGS

These catalogs result from observing programs that contain the procedures described above for absolute programs except that the zero points are defined relative to some other catalog, and determination of the fundamental azimuth is not always included in the program. These catalogs have internally consistent systems, but require an external calibration source to fix the zero points. Quasi-absolute catalogs are not necessarily derived from transit circle observations, and in fact some of the best, most notably HIPPARCOS and the astrolabe catalogs, are derived from other instrumentation.

2.3. DIFFERENTIAL CATALOGS

Catalogs that have been compiled using the star positions of another catalog as reference stars are termed differential. Each night's observations are generally a mix of program stars and reference stars, and the reductions are made relative to the reference catalog. These comments apply to observations made over both wide angles by transit circles and narrow fields by astrographs.

The three basic kinds of catalogs just described are summarized in Table 1.

TABLE 1. CHARACTERISTICS OF CATALOGS

TYPE OF CATALOG	CHARACTERISTICS	CONTRIBUTION TO THE SYSTEM
ABSOLUTE	Rigid frame	
	Instrumental calibration	Zero points
	Nightly calibration	
	Fundamental azimuth	System definition
	Clock star observations	
	Linkage of nights	Individual positions
	Latitude, flexure and refraction solutions	and proper motions
	Solar System objects	
QUASI-ABSOLUTE	Rigid frame	
	Same calibrations as absolute	System Definition
	Clock star observations	
	Linkage of nights	Individual positions
	Flexure, refraction solutions	and proper motions
DIFFERENTIAL	Basic instrumental calibration	Individual positions
	Reference stars	and proper motions

3. THE WASHINGTON FUNDAMENTAL CATALOG

The FK5 represents a considerable improvement over its predecessor, the FK4, with a corrected zero point in right ascension, incorporation of new

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astronomical constants, and significant improvements in the individual positions and motions of the stars, especially in the Southern Hemisphere. In compiling the catalog Solar System observations from absolute catalogs were combined with other data to make the correction to the FK4 equinox. The stellar data of the absolute and quasi-absolute catalogs were then used to correct warps in the system of FK4 positions and motions. Differential catalogs were reduced to the new system to improve the positions and motions of the individual stars (Schwan 1988).

The system of the FK5 was developed by using catalogs not available at the time the FK4 was compiled to correct the FK4 system. Thus the desired continuity in the FK series was maintained. The FK5 has now served the astronomical community extremely well for the better part of a decade.

The decision to begin work on a fundamental catalog at the U.S. Naval Observatory in Washington, the WFC (Cole and Yao 1989), was based on two factors. First, it was felt that it would be desirable to compile a fundamental catalog whose zero points are defined only by direct comparison between the absolute catalogs compiled since 1900 and the standard ephemerides for Solar System objects, currently DE200. Second, there are a number of important catalogs that can be used for the compilation of the WFC that were not available when the FK5 was prepared. In particular, the USNO Pole-to-Pole program (absolute) and HIPPARCOS (quasi-absolute) can be incorporated in the WFC and, respectively, will make very strong contributions to the zero points and definition of the system. Finally, recent work at the USNO has shown that FK5 Equinox appears to be in error by about −130 mas at the epoch of the W1J00, the absolute catalog observed on the Washington 6-Inch Transit Circle from 1977 to 1982. The work has been planned to proceed in three steps which will define the zero points, the system and the individual positions and motions of the WFC.

3.1. STEP 1

The zero points of the WFC will be determined through a comparison of Solar System observations and DE200. The observational data are found mainly in the Cape, Greenwich, and Washington series of absolute catalogs observed since 1900, and in all 33 catalogs are currently being analyzed. In each case it is first necessary to ensure that the Solar System observations are on the same instrumental system as that of the stars. Each observation is then differenced from the DE200 ephemeris values at the time of transit. This provides a direct link between the instrumental system and the Dynamical System, the results of which can be applied to the observed positions of the stars.

Each of the catalogs is evaluated separately and the zero point corrections derived for the mean epoch of observation. Minor planets are to be included if observed in the catalog, but many of the earlier catalogs either have too few of these to be useful or do not include them at all. A solution is made for each of the objects separately in each of the catalogs and then combined to give final corrections to each catalog's equinox and equator. This procedure has been developed by Z. Yao at the USNO using the data of the W1J00.

When the catalogs have been adjusted to the zero points of DE200, they are combined to give stellar positions and proper motions. The zero points of these positions and motions should coincide with those of the DE200 over a wide range of epochs. The positions and motions will first be used to make a final adjustment to the equinox and equator of each of the Step 1 catalogs. This prepares each catalog for Step 2 by bringing it into coincidence with the mean zero points of the system.

3.2. STEP 2

The data of step 2 come from a combination of absolute and quasi-absolute catalogs. The same procedure that was applied to the absolute catalogs at the end of Step 1 must also be used for the quasi-absolute catalogs. This again is a rotation into the zero points of the mean system at the observed epoch of each catalog using the positions and proper motions from Step 1.

An important part of the Step 2 data will come from sources other than transit circles. First of all HIPPARCOS is expected to receive extremely high weight in both the Step 2 and 3 solutions. This will undoubtedly mean that the mean epoch of the system will be within a few years of that of HIPPARCOS. Second, there are results from astrolabes that are also expected to make a significant contribution to the quasi-absolute data of Step 2, in particular the series of observations from China and France. The quasi-absolute transit circle data come mainly from the republics of the former Soviet Union, Chile, Japan, South Africa, Australia Argentina, France, Germany, England, Denmark, Spain, and the United States.

It should be noted that, as in Step 1, the adjustments to the catalogs are rotations, and no corrections are made to the catalog systems. The combination of this considerable body of data will give positions and proper motions that will define the system of the WFC.

3.3. STEP 3

At this stage the differential catalogs are reduced using the output of Step 2. In this step the catalogs are reduced in detail to the WFC system, and these catalogs contribute only to the positions and motions of the individual stars. However, there is a large body of differential data. Many of the catalogs are at early epochs and will be important for the quality of the individual proper motions.

Each of the above steps will include faint (to 9th magnitude) as well as bright stars. Thus another important way in which the WFC will differ from FK5 will be in the magnitude range and number of stars that define the system. The FK5 has been issued in two parts. The first part contains the same stars as the FK4, and it is these stars that define the system of the FK5. The second part, The FK5 Extension, has been compiled differentially and reduced to the FK5 system. Thus the system of the FK5 is defined by the bright stars, and this system is extended differentially to the 9th magnitude. The FK5 and the WFC are compared in Table 2.

If the goal of including the fainter stars in the definition of the zero points and system of the WFC is to be realized, then there must be sufficient observational histories for these stars in Steps 1 and 2. Preparation of the database for the WFC by C. Cole at the USNO Black Birch, New Zealand, station indicates that Step 1 will contain about 15,000 stars, most of which are 7th magnitude or fainter. The first version of Step 1 is scheduled for completion in the first half of 1995. Since the final catalog will contain the stars of the AGK3R+SRS (IRS), FK5 Basic, and FK4 SUP, it will contain almost 42,000 stars, and some 85% to 90% of these will make up Step 2, or at least 35,000 stars.

TABLE 2. Comparison of FK5 and WFC

	FK5	WFC
ZERO POINTS	Corrected FK4 equinox	Defined by absolute catalogs and DE200
SYSTEM	Improved FK4	Defined by combined absolute and quasi-absolute catalogs
SYSTEM DEFINITION	Basic - bright ($m < 7$) 1,535 stars	Bright and faint 35,000 stars
SYSTEM EXTENSION	FK5 Extension (to $m = 9$) Differential 3,117 Stars	Additional 6,000 stars from step 3

4. THE FUTURE OF THE WFC

When work on the WFC based on the Dynamical System is completed, it will be necessary to consider a revision based on the extragalactic reference frame. If the HIPPARCOS proper motions can successfully maintain the HIPPARCOS frame up to 80 or 90 years from the mean epoch, then HIPPARCOS rotated into the extragalactic frame can be used to reduce the earlier catalogs to that frame. However, the proper motions should be tested first by new, high-precision results from optical interferometers. Results from such instruments as the USNO Optical Interferometer over the next two or three years should have the necessary accuracy and be far enough from the HIPPARCOS epoch to provide the necessary check. If necessary, the system of HIPPARCOS proper motions could be adjusted by incorporating these new results. At that point the whole of the WFC database could be converted and thus the highly accurate WFC proper motions would be brought into the extragalactic frame.

5. ACKNOWLEDGMENT

The conception and initial direction of the WFC project came from Dr. C. A. Smith. Until the time of his death in May of 1993 he continued to contribute valuable insights and suggestions. Those of us who continue the compilation of the WFC do so with the acknowledgment of his importance to the success of the work.

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