CHAPTER 18

Fundamental Star Systems

UNTIL the early nineteenth century, the best available fundamental observational catalogs were used directly as reference systems. However, the proper motions, which are an essential part of a complete reference system can be obtained only by a comparison of different catalogs constructed at successive epochs. Moreover, an individual observational catalog is inevitably liable to relatively large errors, because in practice it is not to be expected that the instrumental and observational errors can be perfectly determined and completely eliminated by the corrections and adjustments applied to the observations in forming the catalog. By intercomparing a large number of different catalogs which have been constructed at different observatories and at successive epochs, corrections may be determined for the errors peculiar to each catalog; and from the positions in the separate catalogs, by means of adjustments for these corrections, positions and proper motions may be derived from which the errors, particularly the systematic errors, of the individual catalogs have been as nearly as possible eliminated. A catalog constructed by the adjustment and combination of a number of different observational catalogs is called a *general catalog*. When constructed from fundamental observational catalogs, it is a *fundamental general catalog*, and this is the means now always used to define a standard fundamental star system.

The Construction of a Fundamental System

The separate observational star catalogs that are available for the purpose of constructing a fundamental star system comprise a collection of very heterogeneous material because of the great diversity of instruments and methods that were used in making them. The reduction of the various catalog positions to a uniform system, and the derivation of the best obtainable positions and proper motions from them, are lengthy and difficult. An established standard procedure is followed which in general outline is always the same; but the detailed processes required in applying it to any particular case depend so largely on circumstances, especially the peculiarities of the individual catalogs that are to be combined, that the construction of

each general catalog is in large part practically a special problem in itself. Moreover, the adjustment and combination of different catalogs into the best obtainable composite system depends as much upon a high degree of skill and mature judgment derived from extended experience as upon the actual technical procedures. Only a very general description can therefore be given. The details of the practical procedures that have been used in constructing different specific catalogs may usually be found in the published accounts of each catalog.

The Comparison of Star Catalogs and Their Reduction to a Homogeneous System

The tabulated right ascension and declination of any particular star in an observational catalog is the position in which the star was observed to be at the epoch of the observations, i.e., at the mean of the times at which the individual observations of this star were made, referred to a mean equinox and equator near this time of observation. The positions of the same star from different catalogs form a series of positions for successive epochs which, if there were no errors of observation, would differ from one another only because of precession and proper motion; by reducing them to a common equinox and equator, the proper motion could be derived. However, the actual differences between the coordinates of the same star in different observational catalogs are partly due to both systematic and accidental errors of observation, and before reliable proper motions or definitive positions can be derived the differences must be analyzed to determine and eliminate these errors as much as possible.

The presence of systematic errors is indicated by regularities which are in general found when the positions of a large number of stars in one catalog are compared with the positions of these same stars in another catalog, and the difference found for each star. If the errors of observation were entirely accidental, the mean of these differences should approach zero as the number of stars compared increases. Instead, it usually converges toward some definite positive or negative value that is different according to the different groups of stars selected for comparison—e.g., within each 5° zone of declination, the tabulated declinations of the same stars in the two catalogs may, on the average, differ by a significant amount which varies regularly from zone to zone; or, similarly, the stars within each hour of right ascension, or of each magnitude, or in each of some other type of group may be distinguished on the average by systematic differences between their positions in different catalogs.

These systematic differences between catalogs are the resultant effect of many different causes, often obscure, that influence different groups of star positions in different ways. Discrepancies may be produced by differences

in the selection of clock stars and in the positions adopted for them; moreover, some observational catalogs are not completely fundamental in right ascension, no corrections to the right ascensions of the clock stars having been determined. In some cases, screens were not used to eliminate the magnitude equation. A variety of values for the constants of nutation, aberration, and refraction have been used at different times in reducing observations; and the adopted latitude of the instrument may have been in error. Of primary importance are the systematic differences produced by the individual peculiarities of the different instruments and observers—e.g., the division errors of the circle, which may have been neglected or poorly determined; diurnal temperature effects on the clocks, especially in the case of the older catalogs, and on the instrument itself; various types of personal equation; and so on. Systematic errors often seem to occur for which no apparent explanation can be found.

By appropriate intercomparisons of different observational catalogs, mean corrections for various groups of stars in each catalog may be derived that will reduce the positions of all the stars in the different catalogs to general agreement except for discrepancies which are of an accidental character; and this is the only method by which many of the possible systematic errors may be detected, and their nature and amount estimated. The introduction of corrections to catalogs for the systematic differences among them was largely due to the work of Auwers about 1865. The adjustment of the differences must to a large extent be empirical; the processes used are for the most part tentative, depending on the individual case, and from the very nature of the problem the exact values of the corrections must remain more or less in doubt. An exhaustive study of each catalog is necessary—an examination of the minute details of the methods of observation and reduction, a thorough investigation of the peculiarities of each instrument and the personal equations of the different observers, and an analysis of the peculiar characteristics of the discrepancies between this catalog and the others with which it is compared. The investigation demands an experienced astronomer who is thoroughly familiar with methods of observation and who has a detailed knowledge of all the refinements of the theory of errors.

The particular systematic corrections that are ordinarily determined include, among others, the same ones that are usually determined when, in constructing an observational catalog, corrections to the positions in an adopted catalog are found by observation instead of by comparison with other catalogs—an equinox correction, corrections to right ascension that depend on the right ascension itself and corrections to right ascension that depend on declination, and corrections to declination depending both on right ascension and declination—and much the same processes are used. For example, in determining the corrections to right ascension and declination

that depend on the declination, the differences between the positions of the same stars in different catalogues are grouped according to zones of declination, and the means for the zones plotted against declination and fitted to a smooth curve. In practice, either some one selected catalog may be compared with each of all the other catalogs, or a comparison may be made between pairs of catalogs for the same epoch. In either case, the mean difference between every two catalogs is found; and from a properly weighted mean of all these means, the systematic correction to be applied to all the stars in each catalog may be derived.

Combination of Catalogs into a Fundamental System

After observational catalogs for a series of epochs t_i have been corrected for systematic differences among them, the resulting positions of each star may be considered to differ from one another only by the effects of precession, proper motion, and accidental errors of observation. When these positions are all reduced to a common equinox and equator, the proper motions μ_α, μ_δ and the position (α_0, δ_0) at some selected epoch T_0 may be derived by means of a least square adjustment.

Except for stars with large proper motions in high declinations, it is in general sufficient to assume that the proper motions in right ascension and declination referred to the same equinox and equator are constant. Then the coordinates from each catalog α_i, δ_i for the epoch of observation t_i, referred to the equinox and equator of an epoch T_i, when reduced for precession only to the values $(\alpha_i)_0$, $(\delta_i)_0$, relative to the equinox and equator of the adopted standard epoch T_0, give equations of condition of the form

$$(\alpha_i)_0 = \alpha_0 + \mu_\alpha t_i, \qquad (\delta_i)_0 = \delta_0 + \mu_\delta t_i.$$

In solving these equations by the method of least squares, the star positions from each catalog are suitably weighted on the basis of the estimated precision of the catalog.

Rigorously, the proper motion thus obtained is the value at the mean of all the epochs, referred to the celestial pole of the epoch T_0. The observed positions (α_i, δ_i) are independent of proper motions; but in reducing them for precession to a common epoch T_0, the value of the precessional change depends upon the coordinates and hence, strictly speaking, on the proper motion.

Equivalently, instead of reducing each observed place to the epoch T_0, it may be more convenient to adopt a provisional place for T_0 or some other epoch, then reduce it to the date of each observed place with a provisional proper motion, and compare the results with the actual catalog values. From the differences, corrections may be derived to the adopted provisional

values; the required corrections to the coordinates may in general be assumed to increase linearly with time, and the process is formally the same as before.

For stars with large proper motions or high declinations, procedures of the same nature but with more rigorous formulas may be used.

The derived positions (α_0, δ_0) define a coordinate system at the epoch T_0, and the proper motions provide the means for projecting this coordinate system to other epochs. The proper motions are equally as essential as the catalog positions in using the stars as reference points, and moreover are of direct importance in themselves for problems of stellar dynamics and the structure of the galactic system. However, in even the best modern catalogs the proper motions are far less accurate than the positions at the epoch. The systematic and random errors in the proper motions cause the extrapolated positions to become increasingly uncertain with time, until they are completely inadequate for precise applications. The useful life of a fundamental catalog does not exceed 25 years, and a complete revision is then necessary. For this purpose continued observations of the fundamental stars with meridian circles are necessary to increase further the accuracy of the fundamental system, particularly the proper motions.

The established practice of including the elliptic aberration in the mean place does not introduce any significant error into apparent places. However, the effects of the secular variation of the elliptic aberration are included in the proper motions deduced from mean places; it may eventually become necessary to take this into consideration in statistical investigations of proper motions when sufficiently high precision has been reached in the determination of large numbers of proper motions.*

The Principal Fundamental Systems

In the successive fundamental catalogs which have been constructed since the beginning of the nineteenth century, the earliest observations that were used were those made by James Bradley at the Greenwich Observatory during 1750–1762. Previous observations were not sufficiently accurate for this purpose, particularly for the determination of proper motions. Bradley's observations were first completely reduced, and combined with later observations to form a catalog by Bessel.†

Among the catalogs constructed later in the century, the fundamental systems developed by Newcomb and by Auwers were especially important. In 1872 Newcomb published a catalog of the right ascensions of 32 equatorial fundamental stars determined from 12 independent observational catalogs

* Cf. A. Danjon, "Astronomie Générale," 2nd. ed. p. 108, J. and R. Sennac, Paris, 1959.

† Bessel, "Fundamenta Astronomiae" (1818).

based on observations extending from the time of Bradley to 1870. This was later developed into a complete catalog of 1098 standard stars; and finally in 1898 Newcomb published* a fundamental catalog of 1257 stars, prepared at the request of the Paris Conference of 1896, based upon a thorough discussion of 43 independent observational catalogs, 1755–1895. The positions of the stars from this catalog were used in the national ephemerides until 1925; Newcomb's system was also used in the discussions of the observations of the Sun, Moon, and planets upon which Newcomb, Hill, and Brown based their planetary and lunar tables.

In 1879, Auwers published a fundamental catalog for the northern sky, constructed from several observational catalogs, especially those of Pulkovo and Greenwich, with proper motions determined by comparing the Greenwich observations of 1861 with a new reduction of Bradley's observations. Later, Auwers prepared a further catalog for the southern sky. After several revisions, these catalogs were developed into the "Neue Fundamentalkatalog des Berliner astronomischen Jahrbuchs," prepared by J. Peters (*Veröff. d. astr. Rechen-Instituts*, Nr. 33, 1910). This system, known as the NFK, contains 925 stars, and was based on observational catalogs from the time of Bradley to about 1900.

A revision of the NFK was published in 1937, with the title "Dritter Fundamentalkatalog des Berliner astronomischen Jahrbuchs" (*Veröff. d. Astr. Rechen-Instituts*, Nr. 54). This system, known as the FK3, contains 1535 stars, and was based on 80 independent catalogs from 1820 to 1930. The proper motions were based entirely on observations from 1850 to 1925. The systematic errors in modern fundamental catalogs are principally the result of erroneous proper motions produced by the systematic errors in the observational catalogs that were made before about 1850. The FK3 was in international use from 1940 to 1964, when it was replaced by another revision known as the FK4.

The GC System

The most comprehensive star system is the "General Catalogue of 33342 Stars for the Epoch 1950,"† known as the Albany General Catalogue or GC. It is based on nearly 250 catalogs from 1755 to 1932; in addition, all the stars were reobserved.

The GC is a revision and extension of an earlier "Preliminary General Catalogue of 6188 Stars" prepared by Lewis Boss at the Dudley Observatory in Albany, New York, and published in 1910. The construction of the GC was carried on under the direction of Lewis Boss until his death in 1912,

* S. Newcomb, *Astr. Pap. Amer. Eph.* VIII (1898).

† Carnegie Institution of Washington Publ. No. 468, 5 vols. Washington, D.C., 1937.

and was completed by his son, Benjamin Boss. The observations of the northern stars were made at Albany between 1907 and 1918; they were interrupted during 1909 and 1910 in order to erect the meridian circle at San Luis, Argentina, and observe the southern stars.

The equator was fixed by adjusting catalogs made at observatories in the northern and southern hemispheres; the stars in a large zone near the equator were reobserved from both hemispheres. No use was made of observations of the Sun and planets.

The N30 System

The construction of a fundamental star system to serve as a reference system is an integral part of the development of planetary theories and tables. A revision of the positions and proper motions of the fundamental stars was undertaken by H. R. Morgan at the U.S. Naval Observatory in connection with a cooperative project for the reconstruction of the planetary tables which was inaugurated in 1947 by the Nautical Almanac Office, the Yale University Observatory, and the Watson Scientific Computing Laboratory, with the support of the Office of Naval Research. The primary purpose was to provide a basis for the discussion of the accumulated observations of the planets; but the improved proper motions also provide a basis for further investigations of precession, solar motion, and galactic rotation.

In the construction of the FK3 and GC systems, and the earlier systems upon which they partly depend, the past observations have been successively reduced and discussed so thoroughly that no further discussion of these observations appeared to be necessary. Accordingly, a completely independent system of positions was constructed from the more recent observations, without any use of the proper motions in previous catalogs. Fundamental normal positions independent of all previous determinations were formed for an epoch around 1930 from about 30 fundamental observational catalogs for a few hundred stars. This normal system is designated as N30. The equinox and equator of the normal system were determined from fundamental observations of the Sun, Moon, and planets, principally at Greenwich, Washington, and the Cape Observatory. Proper motions independent of any previous determinations were found by comparing the N30 positions with positions around 1900 taken from the GC or from other catalogs reduced to GC by systematic corrections.

Based on this system a catalog of 5268 standard stars, spaced fairly uniformly over the celestial sphere, was constructed from more than 70 catalogs with mean epochs from 1920 to 1950.*

* H. R. Morgan, Catalog of 5,268 standard stars, 1950.0, based on the normal system N30. *Astr. Pap. Amer. Eph.* **XIII**, Pt. III (1952).