PART I

OBSERVATIONS

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ASTROMETRIC OBSERVATIONS

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If one wants to study the physical characteristics of individual asteroids, he must first find them and be prepared to track them accurately during observation. To make the necessary predictions, the positions of asteroids are measured in reference frames defined by stars of known coordinates as the input information for calculation of orbits and ephemerides. Continuation of positional observations over lengthening arcs provides the basis for improvements of orbits and increased accuracy of ephemerides.

Direct photographs, from which positions relative to background stars are measured, may be made with relatively short-focus instruments of wide field. Astrographs with multicomponent lenses of various designs or catadioptric systems of the Schmidt or Maksutov type are in common use. Typical instruments have fields of several degrees diameter and reach to 16 to 17 mag on plates of scale 1 to 3 arcmin/mm. The overwhelming majority of astrometric observations of minor planets are obtained with such instruments. On a wide-field plate, images of a number of minor planets are usually found in all ecliptic fields; with powerful instruments the number may be very large.

A limited number of faint objects of compelling interest may be observed with powerful long-focus instruments such as the 154 cm *f*/13.5 NASA reflector of the Catalina Station of the Lunar and Planetary Laboratory. Observations of objects as faint as 20 to 21 mag can be obtained with this instrument, but the limited field (30′ at scale 10 arcsec/mm in the focal plane) restricts its practical use to special objects for which a fairly reliable prediction of position (within 5′ to 10′) can be made.

Particularly for faint objects observed at long focal length, it is nearly essential that the motion of the asteroid be compensated during the exposure. On plates taken by this "Metcalf method," star images appear as trails whose length corresponds to the amount of the differential motion during the exposure. The asteroid of perfectly matched motion appears as a small round dot. If asteroids are relatively bright, or the optical system very fast, exposures may be guided carefully on a star, in the same way as for conventional astronomical photography. The moving object will almost invariably appear elongated to some degree on plates taken by this "Wolf method."

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Identification of moving objects on long-focus plates is usually a trivial matter, for normal exposure durations and scale in the focal plane lead to conspicuous displacements. For observations made with wide-field instruments of short focal ratio, it may be necessary to examine pairs of plates rather carefully with a blink comparator to locate all objects of interest. This process may be very tedious, often taking many times longer than acquisition of the plates at the telescope. Even when they are not needed for blink examination, there are many advantages of taking plates in pairs. Photographic defects can be recognized immediately, the reality of near-threshold images is easily tested, and a check on identification of the asteroid as well as on reduction calculations is obtained through comparison of the observed and calculated motions.

Although automatic measuring engines are being used to an increasing degree in measurement of astronomical plates, most such machines are limited in the dimensions of images with which they can deal. This limit is typically of the order of 250 μm. Thus images of moving objects, or of stars on plates taken by the Metcalf method, presently require hand measurement. In our normal procedure, whenever images are sufficiently elongated to degrade the accuracy of direct bisection, the ends of the trails are measured instead. The mean is then taken as representing adequately the position of the star (or of the moving object) at the midexposure time. In exceptional cases of very rapid motion, we have interrupted the exposure for some seconds at the midtime to produce an astrometric reference point. This procedure was followed, for example, on the recovery plates of 1566 Icarus in June 1968. On those plates the motion during the 8 min of exposure needed at the Catalina 154 cm telescope to produce recognizable images of the minor planet, then of 16 to 17 mag, led to star trails 16 mm long.

For hand measurement of plates of ordinary good quality, projection-type measuring engine viewing systems are generally quite satisfactory. But for plates of inferior image quality–heavily fogged in moonlight, weakly exposed, or distorted images–machines arranged for direct viewing by a monocular or binocular microscope provide far better control over contrast and image visibility.

Although it may be unnecessary to mention it, it has occasionally been forgotten that the *time* of the observation is as essential to an astrometric observation of a solar system object as are the coordinates of right ascension and declination. The *mean* of the beginning and end times of the exposure is the appropriate parameter. The accuracy needed in the time will depend upon the rate of motion, but it is conventional to give an accuracy of 1 s unless the rate of motion is such as to make that insufficient.

Reductions of position are made with respect to background stars for which coordinates are available from an appropriate catalog. On wide-field plates, sufficient stars for reduction can almost invariably be found in such a source as the very convenient Smithsonian Astrophysical Observatory (SAO) *Star*

Catalog (1966). This catalog contains the positions and proper motions of 258 997 stars (an average of 6 deg^{-2} over the sky) for the epoch and equinox 1950.0, compiled from a considerable number of fundamental and zone catalogs and reduced, insofar as possible, to a homogeneous system, that of the FK4. Charts are available (SAO, 1969) that greatly facilitate identification of reference stars.

A catalog such as the SAO *Star Catalog* does not contain enough stars to give an adequate reference frame within the very limited field of long-focus reflectors. Further, zone stars will usually be too bright to measure on plates taken for objects of 17 to 21 mag. The many volumes of the *Astrographic Catalogue* (see the brief description by Van Biesbroeck, 1963), the joint enterprise of a number of observatories, may provide a satisfactory reference star system for such plates. As an alternative, it may be necessary to determine coordinates of a suitable set of reference stars by measurement with respect to zone stars on a wide-field plate.

Appropriate procedures to make the transformation from rectangular coordinates measured on the plates to the astronomical coordinates of right ascension and declination depend on the geometry of the projection of the sky onto the photographic plate or film, and thus on the nature of the telescope optical system. Many detailed treatments of this problem have been published; a general review of the standard procedures has been given by König (1962). Over limited fields, even with Schmidt cameras, the linear transformation between measured and tangential coordinates may give satisfactory results. If reductions to high accuracy are required over large fields, more sophisticated procedures may be required. It may be necessary to represent more accurately both the projection geometry and the correction terms that stem from imperfect adjustment of the optical system, variations of refraction and stellar aberration across the field, scale differences arising from color variations among stars, optical aberrations of the telescope, and the like. The field correctors often used with long-focus Cassegrain telescopes, and the field flatteners used with Ritchey-Chrétien telescopes, characteristically introduce a radial scale term that can be fairly large. For examples of recent discussions of these more complex astrometric problems, see Dixon (1962, 1963), Eichhorn et al. (1970), and Kristian and Sandage (1970).

No matter what the source of reference stars and the reduction procedure, it is highly desirable to introduce redundancy into the solution for checking purposes. Even such gross mistakes as misidentification of reference stars do sometimes occur. In the vast work of the *Astrographic Catalogues* (AC or sometimes, somewhat incorrectly, CdC), misprints in both star coordinates and plate constants can be found. Because some plate epochs are as remote as the 1890's, accumulated proper motions are a principal source of error, often leading to residuals of individual stars of 1″ to 2″ from a "best" solution. The epochs of observation of the reference stars from which the *Catalogue* preliminary plate constants were determined, usually without correction for

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proper motion to the epoch of the AC plates, were even more remote. This situation is being remedied for the northern sky as good proper motions for the reference stars become available with completion of the AGK3. New plate constants for the *Astrographic Catalogue* zones north of +40° have been published by Günther and Kox (1970*a,b*), and for the zone from +35° to +40° by Eichhorn and Gatewood (1967). Work on zones south of +36° (to −2°), under the direction of P. Lacroute, is progressing as results from the AGK3 become available. Improvement in the southern hemisphere will have to await improvement of the observational histories of stars defining the fundamental coordinate system.

The use of field plates for determination of coordinates of intermediate reference stars in a good modern catalog system would give a higher accuracy than direct use of the *Astrographic Catalogue* for reduction of long-focus plates. The labor involved in the measurement and reduction is significantly greater, however; and because it would be necessary to acquire the additional plate material with a different instrument, immediate measurement and reduction might be precluded in some circumstances. By such methods one could, in principle, aim for positions good to something like ±0″.5 in special cases in which improvement in accuracy might be critical for success of space missions. It would be useful to have available a list (hopefully short) of potential targets for which high accuracy might be required.

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DISCUSSION

BRATENAHL: How precisely could the positions of an asteroid–Eros, for instance–be measured?

ROEMER: It would be reasonable to go to $0\rlap{.}''5$, or possibly even to $0\rlap{.}''2$, if circumstances justified the special effort that would be necessary.