REFERENCE FRAMES FOR MINOR PLANETS, COMETS AND SATELLITES

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ASTROMETRIC OBSERVATIONS

Because of relatively large orbital inclinations of some minor planets and many comets, coupled with occasional close approaches to the Earth, it may be necessary to measure positions of these objects anywhere in the sky. Brightnesses range widely, some comets becoming bright enough to be readily visible with the naked eye, while small or remote objects challenge the limit of detectability at the largest telescopes. The brightness of a given object observed over an interval of time also will vary, sometimes over many magnitudes, as geocentric and heliocentric distances change.

Instruments of various types are used in making astrometric observations. Astrographs and Schmidt cameras cover fields of as much as $6^{\circ} \times 6^{\circ}$. The photographic field of a long focus reflector is typically half a degree in diameter, while a charge coupled device (CCD) used with such an instrument may image a field no more than an arcminute across. Some observations are now made by scanning a strip of sky a few arcminutes wide as the diurnal motion carries the field past a stationary telescope equipped with a CCD.

If the field of view is sufficiently large, astrometric positions may be deduced directly with respect to 6 - 12 reference stars taken from such sources as the SAO Star Catalog (either the 1966 print version, or the 1984 revision available on magnetic tape), the AGK3 or the Cape Photographić Catalogue (CPC). Each of these catalogs reaches to about 9th magnitude and contains an average of six stars per square degree. Photographic observations with the limited field of large reflectors may be reduced directly by using reference stars from the Astrographic Catalogue (AC), which reaches in most zones to 11th or 12th magnitude and contains rectangular coordinates of some 40 stars per square degree. Since epochs of observation in the AC range from 1891 to 1950, unknown proper motions represent a significant source of error. Even larger errors arise from use of the original plate constants printed in the AC volumes. New constants are available for some zones, or they

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may be determined anew using modern observations of reference star positions. For the very small fields of CCDs, positions of faint intermediate reference stars must be determined. The Palomar Sky Survey plates, or the plates of the ESO/UK Schmidt atlas facilitate the necessary field transfers.

A comprehensive discussion of catalogs for cometary astrometry, equally applicable to minor planets, has been given by de Vegt (1984). Eichhorn (1974) has given an excellent survey of the characteristics and use of the Astrographic Catalogue. Marsden and Roemer (1982) have summarized reduction methodology for photographic astrometry, while Harrington (1984) has provided an algorithm for implementing a standard least squares procedure on a small computer.

ASTROMETRIC ACCURACY

Both minor planets and comets move against the background star fields with rates of motion that range from less than 5'/day to more than 1^{o}/day. Thus either the moving object or stars will be trailed during photographic exposures. If there are no irregularities in tracking the field, or changes in image quality during the exposure, positions derived from the averaged coordinates of the ends of trails will correspond to the midtime of the exposure. Several sources of error are evident, for there often are irregularities in tracking, seeing quality fluctuates, and large magnitude differences between the moving object and reference stars compound the problems. In the case of active comets, the possibility exists of a displacement of the center of light from the center of mass.

Reported positions are, by convention, topocentric, in the reference frame B1950.0, corresponding to that of most of the readily available reference star catalogs. They are stated to precision $0^{s}.01$ in right ascension and $0''.1$ in declination. Time is given in UTC to 0.00001 day $\approx 1^{s}$. Typical real accuracy of current photographic observations is 1"- 2". Early experience with CCD observations of minor planets suggests that if scale is sufficient, an order of magnitude improvement in accuracy can be obtained, probably because of very short exposure times for many objects coupled with the possibility of more precise determination of the centroids of images differing greatly in signal strength.

Discoveries of especially interesting fast-moving objects sometimes are made on photographs taken for other purposes. Particularly in such circumstances, uncertainties in the times of observation often represent a serious source of error.

The best obtainable astrometric precision obviously is needed for those objects targeted for spacecraft exploration. Special star catalogs were compiled to support astrometric observations of comets Giacobini-Zinner and Halley. High accuracy is also needed for predictions of ground tracks for observation of occultations of stars by

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minor planets or satellites, currently an important source of data on the dimensions and shapes of these objects. In present practice, predictions essential for the positioning of mobile observing stations can be made to the necessary precision only after the minor planet has entered the field of the star to be occulted, so that the relative positions of minor planet and star can be determined with respect to the same stellar reference frame. Only high-quality star positions, such as those from the IRS (AGK3R and SRS) provide adequate internal consistency for reasonably satisfactory predictions. Few astrographs provide sufficiently wide fields coupled with the plate scale necessary for such demanding work.

ORBITS AND EPHEMERIDES

Starting data for the computation of orbital elements and ephemerides consist of the topocentric coordinates of the moving object as observed on several dates, together with corresponding topocentric position vectors of the Sun, composed of the geocentric solar position vector from the Newcomb theory, combined with the observatory coordinates. The possibility of observations from satellites orbiting the Earth is thereby readily allowed for. Further, the effects of geocentric parallax often strengthen the determinacy of orbits of close-approach objects. It is the responsibility of the person computing the orbital elements to make such adjustments as the reduction from UTC to ET. Relativistic terms were included in the orbital analyses for the spacecraft encounters with comets Giacobini-Zinner and Halley (Yeomans 1984).

Osculating orbital elements are heliocentric. "Original" orbits are of interest in investigations of the origin of comets, and "future" orbits tell of the escape of some comets from the solar system as a consequence of planetary perturbations. Such orbits are obtained by allowing for the effects of planetary perturbations on the inbound or outbound legs of the osculating orbits, and reducing to the barycenter of the solar system.

Ephemerides are given with time argument in ET unless otherwise stated--as was the case for the special ephemerides for comets Giacobini-Zinner and Halley, which were given in UT. Ephemerides published before October 1979 were geometric. By revised convention, those published since that time include the correction for light time. Ephemerides for photographic or CCD observations normally are astrographic. Radio and radar observations require ephemerides in apparent coordinates. Understanding of the exact nature of an ephemeris is important to locating a faint object in a small field, particularly if it has to be done by blind offset from a nearby star. Yeomans (1981) has given a useful table showing the corrections included in the various kinds of ephemerides.

According to present expectation, positions reduced with respect to star catalogs referenced to the frame B1950.0 will continue to be reported in that frame. It is recognized, however, that some highly precise observations of minor planets are being made in such a way that they can be validly reduced to the J2000.0 system. Observations made with the Carlsberg Automatic Meridian Circle in connection with the HIPPARCOS program are examples. The number of such observations undoubtedly will increase in the future, and a separate file is likely to develop naturally. The complete transition cannot be made, however, until star catalogs in the reference frame J2000.0 are widely available, and also until generators of accurate solar coordinates in the frame J2000.0 are developed.

SATELLITES

Faint satellites distant from their central planets, such as Saturn IX and the outer satellites of Jupiter, usually have to be observed with respect to a reference star field in the same manner as minor planets or comets. Such observations then have to be referenced to the position of the planet defined with respect to the stellar reference frame. Close satellites can be referenced directly to the planet, or to other satellites, though special observing techniques, such as the use of occulting or attenuating devices, or the use of diffraction spikes in measuring, usually have to be employed because of large magnitude differences.

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