THE ASTRONOMICAL JOURNAL VOLUME 76, NUMBER 1 FEBRUARY 1971

Lunar Ephemeris and Astrometric Corrections from Occultations

THOMAS C. VAN FLANDERN
U. S. Naval Observatory, Washington, D. C.
(Received 9 September 1970; revised 6 October 1970)

A comprehensive analysis of 7000 occultation observations between 1950 and 1969 has resulted in a set of corrections to the lunar ephemeris and to the fundamental reference system. The results are presented in Table I. The large correction to the location of the FK4 equinox should be noted. The largest periodic term introduced into the lunar ephemeris from any one of these corrections has an amplitude of 0.14 sec of arc. The entire set of periodic corrections may accumulate to 0″.24 in longitude and 0″.18 in latitude.

TABLE I presents a set of corrections to the lunar ephemeris and the fundamental coordinate system derived from occultation observations of stars by the Moon between 1950 and 1969. The analysis of these observations utilized the lunar ephemeris $j=2$, star positions updated to the FK4 reference system, Watts limb corrections (Watts 1963), analytical partial derivatives for the elements, and other refinements. In addition, coordinates of the observers have been corrected to a world geodetic system (Fischer 1968).

Earlier analyses of this type, based on meridian circle observations of the Moon (Van Flandern 1969; Klock and Scott 1970) were impaired by systematic limb-correction effects, differences between geodetic and astronomical coordinates, variable irradiation, and periodic errors in the fundamental reference system. It is planned to rediscuss the meridian circle observations in the light of these known problems in the near future.

Undoubtedly the occultation solution suffers from similar sources of systematic error. However, the corrections in Table I taken as a whole, provide a significant reduction in the residuals of the observations, and are generally in agreement with other recent results, particularly in regard to the fundamental reference system. These corrections should be used in conjunction with corrections to the Moon's secular acceleration (Van Flandern 1970a), secular changes in the other parameters (Martin and Van Flandern 1970), and corrections for use with the Watts charts (Van Flandern 1970b). These will be referred to subsequently as Papers I, II, and III. In particular, note should be taken of the essential indeterminacy of the inclination and eccentricity, as discussed in Paper III. The results of these three papers were used to modify the partial derivatives and/or residuals before beginning the present solution.

TABLE I. Corrections to the lunar ephemeris and fundamental coordinate system (epoch 1960.0).

			m. e.
Equator	ΔQ	$+0''.01$	$\pm\ 0''.10$
Equinox	ΔE	$+0^s.048$	$\pm\ 0^s.004$
Obliquity	$\Delta\epsilon$	$+0''.04$	$\pm\ 0''.04$
Mean longitude	ΔL	$+0.05$	$\pm\ 0.06$
Mean motion (T in centuries from 1960)	Δn	$+2.0T$	$\pm\ 0.7T$
Longitude of perigee	$\Delta\tilde{\omega}$	-0.7	$\pm\ 0.3$
Eccentricity	Δe	$+0.050$	$\pm\ 0.015$
Solar longitude of perigee	$\Delta\tilde{\omega}_{\odot}$	$-5.$	$\pm 11.$
Solar eccentricity	$\Delta e_{\odot}$	-0.09	$\pm\ 0.18$
Longitude of node	$\Delta\Omega$	$+1.6$	$\pm\ 0.5$
Inclination constant	$\Delta\gamma$	-0.06	$\pm\ 0.02$

The equator correction indicates that the declinations of all FK4 stars should be increased by amount ΔQ. This solution, however, has sampled only stars lying within 6°40′ of the ecliptic. A sampling near the celestial equator might lead to a different result, if distortions of the FK4 are very complex. Note that this equator correction should be applied when using the correction to the Moon's latitude indicated in Paper III, since the mean error of the combination of these two corrections is much less than the mean error of either one separately, because the two corrections are highly correlated.

The equinox correction is a constant correction to the right ascensions of all FK4 stars. In principle, it brings the origin of the star right ascensions back to the "actual" vernal equinox at the epoch 1960.0. The correction is surprisingly large, but in agreement with expectations if a large equinox motion is assumed, such as found by Fricke (1967) and in Paper II. Note that the corrections to the other elements, such as mean longitude and mean motion, discussed below, are all measured from the "actual" equinox, which is moving with respect to the FK4 equinox. Note also that failure to correct the FK4 right ascensions would result in the determination of incorrect orbital elements for the Moon.

The correction to obliquity is for epoch 1960.0, and is assumed to have zero rate of change during the 20 years covered by this analysis, since the variation derived in Paper II was considered there to be statistically not significant.

The corrections for mean longitude and mean motion should be used in conjunction with the secular acceleration of Paper I, plus an Ephemeris Time scale equal to $32^s.15$+A.1. They refer to the geometric, or Watts, center of the Moon. It is interesting to note that by chance, the correction to mean longitude is quite small. This is because the location of the "actual" equinox is very near to Newcomb's equinox in 1960, the latter being the origin of longitudes in the lunar ephemeris

(Aoki 1961). The mean error of this quantity comes almost entirely from the mean error of the equinox correction.

The corrections ΔL, $\Delta\tilde{\omega}$, $\Delta\tilde{\omega}_\odot$, and $\Delta\Omega$ may be combined to give corrections to the fundamental arguments of the lunar theory L, l, l', F, D. The last of these, $\Delta D = \Delta L - \Delta L_\odot = -0''.9 \pm 0''.8$, must be interpreted as a correction to the location of the Moon's center of mass with respect to the geometrical center in longitude, discussed in Paper III, assuming that the only correction required to the sun's longitude in Newcomb's ephemeris is the equinox correction, $\Delta E \cos \epsilon$. Rates of change of nodes and perigee corrections are given in Paper II, and $(d/dT)\Delta\tilde{\omega}_\odot$ is taken to be $-6''$ per century, following Lieske (1967).

The eccentricity corrections are expressed in arc instead of radians, and $\gamma = \sin \frac{1}{2}I$, where I is the Moon's inclination to the ecliptic. Hence $\Delta I = 2\Delta\gamma$.

The corrections to solar orbital elements are weakly determined by this solution, but influence the lunar ephemeris noticeably. Unfortunately, they are highly correlated with annual terms in the star right ascensions. The correction to the solar longitude of perigee is especially unstable.

The following corrections to the lunar ephemeris $\geqq 0''.015$ in longitude and latitude, and $\geqq 0''.0015$ in parallax, are implied by the present solution at epoch 1960.0:

$$\Delta\lambda_☽'' = +0.05 + 0.08 \cos l - 0.06 \cos (l-2D) - 0.02 \cos 2D - 0.02 \cos l' + 0.10 \sin l - 0.02 \sin (l-2D) + 0.02 \sin l'$$

$$\Delta\beta_☽'' = -0.14 \cos F - 0.12 \sin F$$

$$\Delta\pi_☽'' = 0$$

In deriving these corrections, the independent variable of the lunar ephemeris is assumed to be $32^s.15 + \mathrm{A.1}$ (Atomic Time), and the reference system is assumed to be that defined by the equator, equinox, and obliquity corrections of this solution. The quantities l, l', F, D are the fundamental arguments of the lunar theory.

REFERENCES

Aoki, S. 1961, *Astron. J.* **66**, 1.

Fischer, I. 1968, *Army Map Service Tech. Report*, No. 67 (Washington, D. C.).

Fricke, W. 1967, *Astron. J.* **72**, 1368.

Klock, B. L., and Scott, D. K. 1970, *ibid.* **75**, 851.

Lieske, J. H. 1967, *JPL Tech. Report*, No. 32-1206 (Pasadena, Calif.).

Martin, C. F., and Van Flandern, T. C. 1970, *Science* **168**, 246 (Paper II).

Van Flandern, T. C. 1969, *Celestial Mech.* **1**, 163.

——. 1970a, *Astron. J.* **75**, 657 (Paper I).

——. 1970b, *ibid.*, 744 (Paper III).

Watts, C. B. 1963, *Astron. Papers Am. Ephemeris* **XVII** (Washington, D. C.).