PRESENT STATUS OF THE ASTRONOMICAL EPHEMERIS

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The IAU (1976) System of Astronomical Constants and a new set of fundamental theories will expectedly be introduced into the international and national ephemerides for the volumes of 1984 onwards. In order to avoid any confusion in the future, it is necessary to manifest the character of the data published in the current volumes of the Astronomical Ephemeris = American Ephemeris, both abbreviated as A.E. With this end in view, computer programs for the calculations of the ephemerides of the Sun and inner planets based on the Newcomb's (1895, 1898) Tables have been prepared at Tokyo Astronomical Observatory (TAO) and Hydrographic Department of Japan (JHD) independently of each other using different computers and hence different types of FORTRAN. JHD has further prepared the programs for the Moon's ephemerides based on the Brown-Eckert theory and has reproduced the Eckert, Brouwer and Clemence's numerical integrations of the outer planets. Fundamental ephemerides thus calculated are compared with those data tabulated in the A.E. for the year of 1975, as an example, in the present paper.

In the Introduction (pp.9 - 20) of the Newcomb's (1895) Tables of the Sun (hereafter called Tables), he gives the basic data and formulas (hereafter called basis) which were used to tabulate the individual values in the main body (called tabulation) of the Tables. However, the actual data in the tabulation are not necessarily consistent with the basis. In addition to the effects due to the rounding-off and the omission of small terms in the tabulation, two causes have been found to explain the discrepancy between the basis and the tabulation: (i) Clemence (1943) pointed out that, in the calculation of the perturbations in longitude by Venus, Newcomb had not used some terms listed in the basis but had purposely adopted other terms which are given in the column "Tables VIII and XII" in Table I of the Clemence's paper, although Clemence could not find the ground of these terms. (ii) Kinoshita et al. (1974) found that the tabulation of the perturbations in longitude by Jupiter might have been calculated as if each numerical coefficient for $j = 5$ were situated by one rank upper in Table D of the basis. The error in the tabulation thus amounts to $\pm 0\overset{''}{.}07$ by (i) and $\pm 0\overset{''}{.}03$ by (ii). The discrepancy in the perturbations in longitude by

R. L. Duncombe (ed.), Dynamics of the Solar System, 115–120.

Mars between the basis and the tabulation amounts to ±0".04 and seems somewhat systematic but its cause has not been found.

In the basis (p. 10) series expansions of the equation of the center and the logarithm of the radius vector are presented and they are almost consistent with the respective tabulations. In this connection, it is remarked that, when we simply apply the Kepler's equation, the coefficients of the series of Log R are practically consistent with the value of the eccentricity e in the basis (p. 9), while in the series of the equation of the center, there appears a discrepancy by (0".004 + 0".007 T) sin 3g which may yield a discrepancy by ±0".010 in λ after 1980.

In principle, both programs prepared at the JHD and the TAO are strictly based on the basis with following modifications for longitude: (a) "Tables VIII and XII" of the Clemence's (1943) paper are adopted for the perturbations by Venus, and (b) the equation of the center and Log R are calculated by solving the Kepler's equation with the value of e in the basis. Although there are several differences between the programs of the JHD and those of the TAO, the discrepancies between their calculated data are less than ±0".001 in λ and β, and ±0.000 000 01 A.U. in the radius vector, namely one-tenth in the units of the respective printed last figures in the A.E.

The programs for Mercury, Venus and Mars have been prepared in the same manner as those for the Sun, being based on the respective bases of the Newcomb's (1895, 1898) Tables with Ross' (1917) correction for Mars. JHD-data and TAO-data agree well with each other within ±0".001 in λ and β, and ±0.000 000 01 A.U. in the radius vectors.

We may thus esteem that both JHD- and TAO-programs for the Sun and the inner planets are strictly consistent with Newcomb's theories. Thereupon the JHD-data are compared with the A.E.-data. Discrepancies AE - JHD in the ecliptic coordinates for the Sun and Mercury are illustrated in Figure 1 as an example. Each pair of horizontal broken-lines in the figure indicates the one-half of the printed last decimal in the A.E. Since the JHD-data are expressed down to the lower decimals than the A.E.-data, individual dots inside the broken-line pair indicate that those A.E.-data agree with the JHD-data exactly at the printed last decimals. For λ and β of the Sun, only the dots on the respective abscissae correspond to the exact agreement at the printed last decimals. Frequency distributions of the discrepancies AE - JHD are presented in Table 1. Its horizontal argument is the discrepancy at the printed last decimals which are listed in the second column.

Most of the A.E.-data of the inner planets seem passable, excepting for the systematic bias in the radius vector of Mercury. We should not underestimate the discrepancies in the Sun's coordinates, any error of which may affect significantly the calculations of the geocentric coordinates of the planets. An example of the transfer of errors is exhibited in Figure 2. Its abscissa denotes the actual discrepancy Δr_M in the geocentric distance r_M of Mercury, and the ordinate denotes the

Table 1. Frequency distribution of AE - JHD

		last decimal in AE	(Units : last decimals in AE) ≤-5	-4	-3	-2	1	0	+1	+2	+3	+4	+5
Sun	λ	$0''.01$	24*	40	55	49	56	24	40	42	21	10	4
	β	$0''.01$			18	34	76	73	89	39	26	10	
	R	E - 7**				13	89	114	119	23	7		
	X***	E - 7				2	49	110	131	58	14		
	Y	E - 7			7	75	89	108	66	18	1		
	Z	E - 7				8	89	191	70	6			
Mercury	λ	$0''.1$					19	312	35				
	β	$0''.1$					8	348	10				
	R	E - 7		1	16	107	161	71	10				
Venus	λ	$0''.1$					10	156	17				
	β	$0''.1$					12	162	9				
	R	E - 7					19	139	25				
Mars	λ	$0''.1$					2	79	11				
	β	$0''.1$					7	81	4				
	R	E - 7					9	52	27	4			
Sun	α	$0^{s}.01$					32	315	18				
	δ	$0''.1$					29	299	37				
Mercury	α	$0^{s}.01$					60	278	27				
	δ	$0''.1$					25	298	41	1			
	r	E - 7		1	22	62	108	96	53	20	3		
Venus	α	$0^{s}.01$					32	284	47	2			
	δ	$0''.1$					36	275	53	1			
	r	E - 7		3	8	15	42	89	93	53	41	19	2
Mars	α	$0^{s}.01$					29	310	26				
	δ	$0''.1$					26	314	25				
	r	E - 7			5	30	64	77	85	63	31	10	
Jupiter	α	$0^{s}.001$					47	240	78	1			
	δ	$0''.01$					55	230	81				
	r	E - 7		3	18	61	87	62	79	46	11	1	
Saturn	α	$0^{s}.001$					42	255	69				
	δ	$0''.01$					44	275	47				
	r	E - 7		3	30	87	116	96	28	5	1		
Uranus	α	$0^{s}.001$					31	287	48				
	δ	$0''.01$					110	239	17				
	r	E - 6					206	160					
Neptune	α	$0^{s}.001$					29	277	59				
	δ	$0''.01$					104	234	17				
	r	E - 6					198	167					
Pluto	α	$0^{s}.001$						222	144				
	δ	$0''.01$					131	224	11				
	r	E - 6					48	316	2				

* -7:5, -6:5, -5:14. ** E - 7 stands for 10^{-7}A.U.
*** Values for the nearest beginning of year. Those for 1950.0 exhibit similar frequency distributions.

effect δr_M due to the discrepancies in the Sun's coordinates and the Mercury's heliocentric coordinates to the calculation of its geocentric distance, i.e.

$$\Delta r_M = r_M(AE) - r_M(JHD),$$

$$\delta r_M = a\delta\lambda_S + b\delta\beta_S + c\delta R_S + d\delta\lambda_M + e\delta\beta_M + f\delta R_M,$$

where $$a = \partial r_M / \partial \lambda_S, \quad \delta\lambda_S = \lambda_S(AE) - \lambda_S(JHD), \quad \text{etc.}$$

We can find a clear correlation between Δr_M and δr_M and a systematic bias.

Numerical integrations of the heliocentric rectangular coordinates of the outer planets have yielded satisfactorily identical data with those by Eckert, Brouwer and Clemence (1951). Only less than 0.5% of data differ from the Eckert et al's data by ± 1 at the printed last

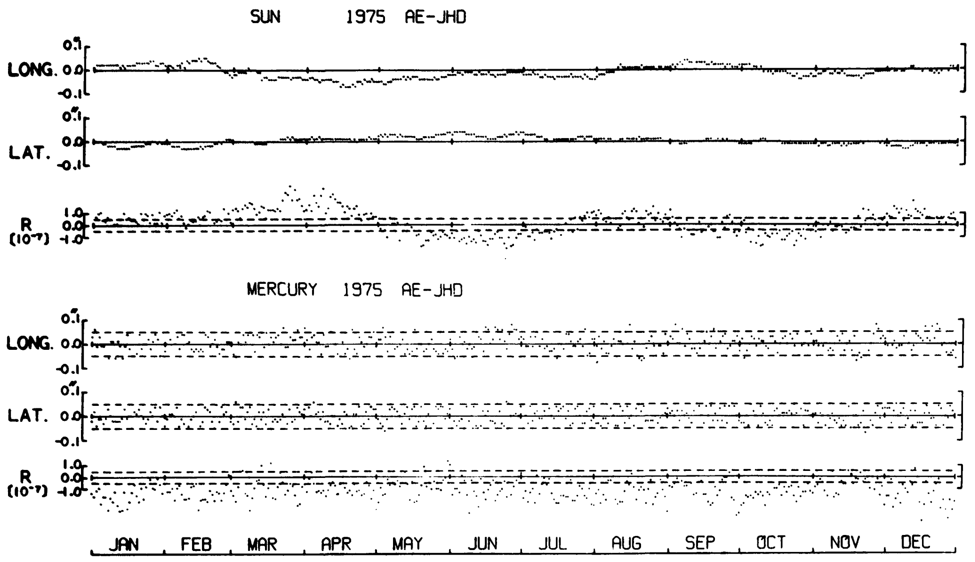


Figure 1. (above)

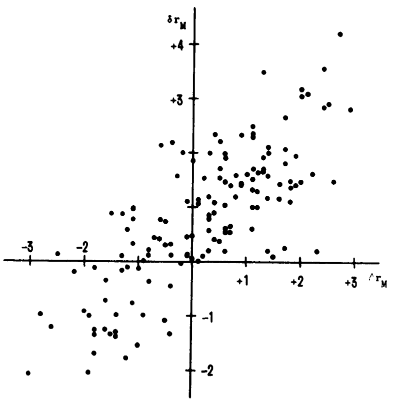
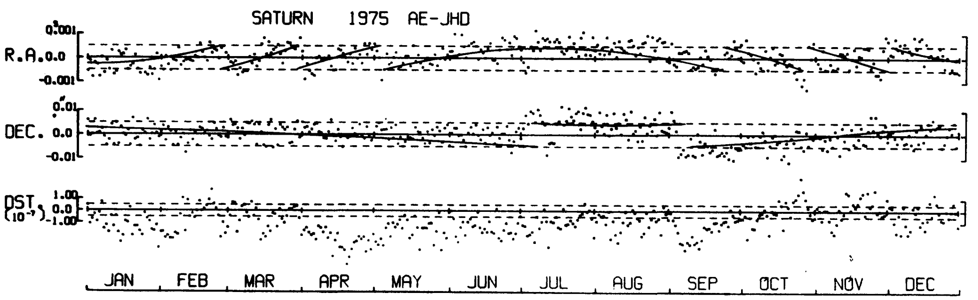


Figure 2. (left)

Figure 3. (below)



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decimal, 0.000 000 001 A.U. Since the heliocentric spherical coordinates in the A.E. do not include the Clemence's (1954) correction due to the perturbations by the inner planets, the comparison with the JHD-data has not been made for these quantities. Discrepancies in the geocentric ephemerides are rather significant. Examples are shown in Figure 3. The discrepancies in α and δ may be mostly caused by (i) discrepancies in the Sun's ephemerides, and (ii) inappropriate procedure of correction in the A.E. due to the change in the value of aberration constant. The latter effect is shown by discontinuous lines in Figure 3. Values of AE - JHD in the geocentric distances of Uranus and Neptune both concentrate strongly in the range between 0 and -1 in the unit of the printed last decimal, suggesting that the A.E. tabulates these quantities by omitting the figures lower than the printed last decimal.

(Note) Numerical integrations for the principal minor planets by Duncombe (1969) have not been traced. Their reduction to the geocentric ephemerides yields higher values in declination than the A.E. by 0".1 constantly when the declination is negative. Erratum for the data from 1972 to 1980 is thus being noticed in the every volume of the A.E. Until the volume for 1971, the A.E. tabulated the geocentric ephemerides deduced from the Herget's (1962) integrations and agrees well with the JHD-calculations.

Programs of j = 2 ephemerides of the Moon have been prepared by Inoue (1977) following the theory by Eckert, Walker and Eckert (1966). The agreement between the USNAO-data (Van Flandern, 1976) and the JHD-data is so satisfactory that their discrepancies are $\pm$0".0002 in λ and β, and $\pm$0".000 002 in π to be compared with their respective last decimals in the A.E. (0".01 in λ and β, and 0".0001 in π). Among all half-day ephemerides between 1973 and 1980, the discrepancies AE - JHD by $\pm$1 at the printed last decimals of the A.E. occur at 8% of data for λ, 21% for β and 5% for π. These discrepancies may be mostly caused by the defects in the A.E.-programs, for example, the incomplete treatment of the corrections for the change in the value of the Earth's flattening.

Programs for nutation are based on the Woolard's (1953) formulas. The JHD-data have been compared with the USNAO-data provided by Van Flandern (1976). Discrepancies between them are less than $\pm$0".000 003 in longitude and $\pm$0".000 001 in obliquity. We may thus esteem that the JHD- and the USNAO-data are both completely strict to the Woolard's formulas. On the other hand, about 30% of the A.E.-data are differ from the JHD-data by $\pm$1 at the printed last decimals (0".001) both in longitude and obliquity. These discrepancies may be attributed to the simplification adopted in the A.E.-calculation schema as explained by Wilkins (1954).

The discrepancies AE - JHD surveyed above might be regarded as passable in the former days. However, with the general availability of computers, we can now calculate the ephemerides as precisely as we wish, whenever the basic theory is given. Agreement between the JHD- and the USNAO-data is its good example. On the other hand, it may be practically difficult to calculate the data which are exactly identical with those printed in the current volumes of the A.E. Hence, we consider that the international ephemerides in the future should be calculated at least at two organizations independently using different types of computer.

The present investigation has been carried out as a collaborative work by many members of the Tokyo Astronomical Observatory and the Hydrographic Department of Japan. The authors are greatly indebted to them. A fuller version of this work will be published in the "Report of Hydrographic Researches", No. 14 (1979) under the names of A.M. Sinzi, K. Inoue, Y. Kubo, Sh. Aoki, H. Kinoshita and H. Nakai.

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DISCUSSION

Henrard: What is the JHD-ephemeris? Is it a new theory?
Sinzi: It is strictly based on the Brown-Eckert theory.

Duncombe: I should like to congratulate Dr. Aoki and Dr. Sinzi on their very thorough investigation. It very clearly illustrates why we need a new basis for the ephemerides in the A.E.

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