C. JOINT DISCUSSION

ON

THE DEMANDS MADE ON CELESTIAL MECHANICS BY THE PREPARATION OF EPHEMERIDES

Monday 21 August 1961 at 14^h00^m

ORGANIZING COMMITTEE: F. Arend, D. Brouwer, R. L. Duncombe, W. Fricke (Chairman), W. Markowitz.

REPORT OF THE PROCEEDINGS

R. L. Duncombe and *G. A. Wilkins*

Introduction

The prepared contributions to the Joint Discussion follow this report in the order of their presentation; one paper will shortly appear in print elsewhere and so only a brief summary is given here. In this report of the proceedings we have endeavoured to give a more connected account of the discussion than would result from a verbatim account of the remarks made after each paper. Of necessity, we have made some omissions and some additions, but we hope that those who were present will find this to be a fair report and that readers who were not present will find it a useful introduction to the papers themselves.

The reference numbers in this report refer to the papers presented during the discussion; the authors and brief titles are as follows:

1. *Wilkins.* Computation of the lunar ephemeris.
2. *Eckert* and *Smith.* Numerical development of harmonic series for the Moon.
3. *Brouwer.* Application of von Zeipel's method to the lunar theory.
4. *Duncombe.* Requirements for planetary ephemerides.
5. *Clemence.* Theories of the motions of Mars and the Earth.
6. *Kovalevsky.* Nécessité d'une nouvelle théorie des quatre gros satellites du Jupiter.
7. *Herget, P.* Ephemeris calculations for minor planets.
   The complete paper will appear in the *Astronomical Journal.*
8. *Rabe.* Improvement of astronomical constants in ephemeris computations.
9. *Markowitz.* Astronomical and atomic time in the observation of artificial satellites.

W. Fricke, President of Commission 4, was chairman for the first half of the discussion (papers 1-5), and D. Brouwer, President of Commission 7, was chairman for the second half (papers 6-9).

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As this list shows the contributions ranged over most of the major aspects of celestial mechanics and of the preparation of ephemerides, but they were only indirectly related to the title of the discussion. An underlying theme of most of the papers was, however, the changes being brought about in these subjects by the widespread use of electronic computers and, less directly, by the introduction of new techniques of observation. Thus computers are now being used at all stages—in the development of the series expansions of fundamental theories (**2, 3, 5**), in the evaluation of these series (**1, 4**), in the direct numerical integration of the equations of motion (**7**), and in the comparison of observation and theory (**6**). Although computers have eliminated much of the drudgery of numerical calculation from celestial mechanics their efficient use requires the introduction of new forms of ephemerides (**1, 4**) and it was even suggested (**4**) that they may eliminate completely the need for extensive fundamental ephemerides.

The Moon

In order to satisfy the immediate requirements for an accurate ephemeris of the Moon for planning purposes in astronomy and space research, H.M. Nautical Almanac Office has undertaken the continuation of the improved lunar ephemeris for the period 1972–81. Wilkins (**1**) indicated the techniques that are to be used, and drew attention to a recurrence relation, first suggested by Sadler, that leads to a very efficient method for the evaluation of harmonic series that is particularly suited to comparatively slow computers. In reply to a question by Hertz, Wilkins stated that there were no definite plans to prepare an ephemeris in rectangular co-ordinates but that this would be done if the demand were great enough.

The current lunar ephemeris is likely to be superseded in a few years time by one based on the re-development of the Hill-Brown theory to higher accuracy at the IBM Watson Scientific Computing Laboratory (**2**). Brown has estimated that his original development for the main problem of the lunar theory required some nine thousand man-hours of computing, and so it will be realized that this re-development would not have been attempted without the aid of electronic computers. It is a tribute to the accuracy of the original work that Eckert afterwards stated, in reply to Brouwer, that so far no significant errors in the coefficients of the periodic terms had been found. Even so the last word on the lunar theory has not yet been uttered and Brouwer (**3**) described the current investigations at Yale into Delaunay's theory and the possible applications of von Zeipel's method.

The Planets

The current intensive work at the U.S. Naval Observatory on the theories and ephemerides of the planets was reviewed by Duncombe (**4**) and the progress with his new theories of Mars and the Earth was described by Clemence (**5**). In opening the discussion on the first of these papers Fricke considered that ten years ago such a paper would have been incredible, and he later drew attention to the great importance of the new theories, particularly that for the Earth. The results already obtained, together with those that we may confidently expect in the next few years will give astronomers new, or revised, theories of the motions of all of the planets—an achievement that is comparable with that of Newcomb and Hill at the end of the last century.

Duncombe also pointed out that the new techniques of radar astronomy now meant that the distances and line-of-sight velocities of the planets, as well as their directions, can now be observed. Already more precise ephemerides are needed for comparison with the observations, and significant improvements in our knowledge of the solar parallax (see below) and of the motion of Venus are being obtained.

Sir Harold Jeffreys asked whether the anomaly about the rate of change of the obliquity was cleared up yet. Clemence replied that the obliquity was varying more rapidly than was expected and that this might be due to the fact that only a first-order theory is now used, and that it will be of interest to see the results from the second-order theory of the Earth.

Machine-readable ephemerides

Duncombe (**4**) drew attention to the growing volume of planetary ephemerides that were available on punched cards at the U.S. Naval Observatory and elsewhere. (A committee, under the chairmanship of Eckert, is at present endeavouring to draw up and circulate a consolidated list of all suitable astronomical data, including star catalogues, that are available in machine-readable form.) Much of these data are, however, in the same format as the printed ephemerides and both he and Wilkins (**1**) considered the possibility of preparing ephemerides that were specially designed for use with electronic computers. Such ephemerides would not only be 'machine-readable', *i.e.* on punched cards or magnetic tape, but would also be 'computer-orientated' so as to require the minimum amount of storage space consistent with ease of use. The discussion that followed these papers showed that the need for such ephemerides is very real and pressing.

Clemence and Eichhorn both asked about the number of terms that would be required in a Chebyshev expansion for the Moon at intervals greater than two days. Wilkins said that the number of terms increased rapidly with the ratio of the interval to the periods of the harmonic terms concerned, and was unable to give any firm estimates. It seems that 12-15 terms would be required for an interval of 10 days and at least 20 terms for 20 days. Sconzo suggested that Hermite polynomials might prove to be more useful.

For the planets Hertz pointed out that heliocentric ephemerides could be given at wider intervals than geocentric ephemerides and he also enquired whether it would be possible to devise a theory that would give the Chebyshev expansions directly. This possibility had been considered by Wilkins but he doubted whether it was practicable, particularly as each Chebyshev expansion is valid only for a finite interval.

Satellites

Kovalevsky presented his paper (**6**), on the need for a new theory of the first four satellites of Jupiter, in French and then gave an excellent summary in English. He emphasised the difficulties of this theory and made a plea for modern observations of these satellites, which, in common with other natural satellites, have been largely neglected by astronomers over the past half century. In response to this plea Brouwer stated, firstly, that he would look into the collection of Yale plates to see if more observations were available and, secondly, that Jackson was preparing to make a new series of observations at Mount Stromlo. Marsden stated that he had tried to make observations of the four satellites of Jupiter with the catalog camera at Yale but that not all the images were measurable. Strand indicated that a series of observations might be undertaken by the U.S. Naval Observatory. Ashbrook pointed out that his collection of approximately 8000 eclipses of the satellites of Jupiter dated back to the seventeenth century and did not include any new data. Herget mentioned that among modern observations is a series by Aitken who measured the positions of the satellites with respect to each other. In reply to a question about the usefulness of such relative positions of satellites Jeffreys stated that he thought that about two-thirds of the observations of Saturn's satellites that the Struve's used were measures of one satellite from another. In reply to another question it was stated that timing usually presents no difficulty as one second was good enough, but that it was difficult to obtain accurate positions of the satellites.

Minor planets

Herget (7) reported on some recent work to improve even further the methods adopted for the ephemeris calculations for minor planets. It is planned to compute perturbations by the variation of elements using a set which has no reference to the perihelion. This requires the computation of the position of a moving 'departure point'. There are no adverse circumstances, either in the case of a very small or a moderately large eccentricity or inclination. A corresponding set of unknowns for differential correction has the property that they are well separated under these same circumstances. In the discussion of this paper both Herrick and Musen indicated that they had also considered similar sets of elements.

Fundamental constants

After discussing the need for ephemerides of high precision Rabe (8) turned to the consequences of the introduction of space-age methods for the determination of astronomical constants. This paper, as well as that of Duncombe (4), was followed by a lengthy discussion of the results of the recent radar observations of Venus. In response to questions Duncombe stated that, while these observations have added significantly to the evaluation of the astronomical unit, perhaps too much weight has been assigned to them and many more observations are required. Clemence remarked that the 1958 determination of the solar parallax from radar echoes of Venus has been withdrawn. Brouwer pointed out that the Soviet radar-echo result was close to the latest American results. Blitzstein quoted a value of the solar parallax of $8''{\cdot}79460$ obtained from the latest RCA observations of the distance of Venus. Herrick emphasised that the ratio of the light-second to the astronomical unit was more important than the solar parallax itself.

Time

The influence of the introduction of new techniques was also apparent in the last paper by Markowitz (9) who considered the possible uses of artificial satellites in the study of time and who emphasised that caesium-beam oscillators can be used to define a system of time much more precisely than Ephemeris Time can be determined. In the discussion that followed it was clear that confusion is sometimes caused by the use of the term Ephemeris Time for the independent variable of the equations of motion as well as for the systems of time defined by the motions of the Sun and Moon. Herrick suggested that it would be better to use the term 'gravitational time' for the former. Clemence was of the opinion that it was sufficient to use the abbreviation E.T. with appropriate subscripts to distinguish special systems of Ephemeris Time; such a suggestion has been adopted by Commissions 4, 17 and 31. Brouwer emphasised that at present we have no check on the lunar theory and that he thought that there was a need for an artificial Earth satellite which could be accurately observed in order to check the values of Ephemeris Time now determined from the Moon. Markowitz suggested that more transit-circle observations of the Sun were needed and he also stated that Commission 31 has now recommended the use of artificial Earth satellites for use in time determinations.