EARLY APPLICATIONS OF COMPUTER TECHNOLOGY TO DYNAMICAL ASTRONOMY

RAYNOR L. DUNCOMBE
Center for Space Research
University of Texas at Austin
Austin, TX 78712

ABSTRACT. The review traces the progress from the early application of the Hollerith Tabulating Machine to the construction of astronomical tables by interpolation and to the evaluation of Brown's Tables of the Moon by L. J. Comrie in the late 1920's and early 1930's to the introduction of large programmable electronic calculators in the post World War II era. The early application of electromechanical punched-card machines to astronomical problems stemmed from the needs of the national ephemeris offices to evaluate theories of the Sun, Moon and planets and to subtabulate these positions to form the tables of daily values given in the national almanacs. These techniques were quickly applied to other astronomical problems such as the construction of star catalogs, the reduction of astrometric observations and the numerical integration of the equations of motion of objects in the solar system.

A suitable subtitle for this short review might be "Blame It On the Moon" because of all of the prominent celestial objects clearly visible in the sky the Moon has proven to be the most troublesome for the theorist and the ephemeris maker. In 1767 when the British Nautical Almanac was started by the Astronomer Royal Nevil Maskelyne, the position of the Moon rested on Mayer's Tables which were accurate enough to permit determination of longitude at sea within a degree by the method of lunar distances. Within a few years, however these tables departed from the true position of the Moon and in spite of repeated attempts to correct them, the predicted positions became less and less reliable. While the British Nautical Almanac was much sought after by sea captains of countries which had no comparable navigational almanacs, the experienced British navigator was beginning to suspect the accuracy of his derived longitudes. D. H. Sadler, former Superintendent of H. M. Nautical Almanac Office told this story of an incident occurring in the late 1700's. A British merchant ship bound for America met in mid-Atlantic with a treasure laden galleon bound for Spain. In the exchange of amenities, the Spanish captain sent over a small chest of gold. The British captain, searching for some suitable gift, sent his only copy of the British Nautical Almanac to the Spanish ship. As the story goes, the English ship with its small chest of gold, made port safely and the Spanish ship was never heard from again.

Celestial Mechanics 45: 1–9, 1989.

A succession of lunar tables followed (Lalande, Laplace, Burckhardt, Hansen) each more accurate than the last but also more complex and more difficult to evaluate. The tedium of extracting positions from such tables is reflected in the plea of the Astronomer Royal John Bond about 1834 in requesting an increase in his staff of assistants: " I want indefatigable, hard-working, and above all, obedient drudges (for so I must call them, although they are drudges of a superior order), men who will be contented to pass half their day in using their hands and eyes in the mechanical act of observing, and the remainder in the dull process of calculation."

The International Congress on Astronomical Ephemerides, held at Paris in 1911, designated the distribution of calculations among the various national ephemeris offices. It was specified that with the exception of the Connaissance des Temps, all ephemerides would utilize Newcomb's and Hill's tables for the sun and planets, and for the Moon, Hansen's tables with Newcomb's corrections until Brown's new tables became available.

That day came in 1923 and with the introduction of Brown's Theory and Tables the drudgery of calculation was greatly exacerbated. In these tables over 1400 periodic terms were combined into 180 separate tables covering 660 pages. While the tables were well arranged, it required the continuous work of two experienced skilled computers, extracting and checking half-daily positions,to barely keep up with the motion of the Moon. L. J. Comrie, Superintendent, H. M. Nautical Almanac Office, who had experimented earlier with the use of Hollerith Electric Punched Card Machines in the construction of tables by interpolation [3], saw their application to the evaluation of Brown's Tables [4]. In 1928 actual punching of tables was started (a daunting task of punching 20,000,000 holes in half a million cards) and in 1929, using a Hollerith Tabulator and Sorter installed at H. M. Nautical Almanac Office, the evaluation of the Tables was carried from 1930 through the end of the century. Comrie pointed out that use of the Hollerith equipment had reduced the drudgery and fatigue, increased the speed by a factor of ten and had reduced the cost by seventy-five percent.

During this same period of time, Wallace J. Eckert, who had joined the Department of Astronomy at Columbia University in 1926, began experimenting with IBM Electric Punched Card Machines at the Columbia University Statistical Bureau [6]. With the addition of special circuits and control devices, he quickly demonstrated the efficacy of the electric punched card method for the solution of problems in astronomy and in 1934 he helped organize the Thomas J. Watson Astronomical Computing Bureau under the auspices of the American Astronomical Society, IBM and the Department of Astronomy at Columbia. The electromechanical machines utilized in the Bureau were ideally suited for batch processing but much less so for serial computations involving more than a few steps. Operations such as interpolation, sub-tabulation, formation of differences and checking the sums of products, for example, were easily performed but a stepwise numerical integration of the equations of motion of a minor planet, for instance, was tedious and time-consuming. For such sequential operations Dr. Eckert devised a piano roll like device which was advanced one notch at each step to alter set-up switches and plug-board wiring for the next operation. Carrying forward a numerical integration by this method might give a modern scientist the piano roll blues, but at the time it was far more accurate and efficient than computations with a desk calculator. In 1939 Dr. Eckert estimated that nearly all astronomical calculations being done by the punched card method were being performed at the Bureau.

At the beginning of World War II, the U. S. Nautical Almanac Office was faced with the requirement to produce an almanac for air navigation, similar to the Nautical Almanac but with the positions of the Sun, Moon and planets tabulated for every 10 minutes of GMT. Again the Moon was the problem. The computational burden was beyond the capability of the Nautical Almanac Office staff at that time so the Navy turned to Dr. Eckert [Fig. 1]. He accepted the position of Director of the Nautical Almanac Office in early 1940 and proceeded to establish the first punched card scientific computing laboratory in the U. S. Government. The initial complement of machines comprised the tabulator with special fractional wheels for adding degrees, minutes and seconds, a reproducing punch, a multiplying punch, a sorter and a key punch. Several years later a collator and an interpreter were acquired. The Electric Punched Card Method proved adequate for the task and the 1941 Air Almanac appeared in September of 1940 [Fig. 2]. Several innovations were introduced in the production process. To avoid the delays and errors of type setting, the printers copy was prepared on the tabulator from a set of cards on which the final data were assembled. The copy was then photographed and reduced to book size and the printing done from deep-etched plates made from the negatives. The proofs were keypunched and compared line by line with the printers copy cards to automatically proofread the data. In spite of alignment problems with the tabulator typebars, the copy was readable, and with introduction of the card operated typewriter, which IBM produced to Dr. Eckerts design in 1945, the results were as perfect as typeset copy [Fig. 3]. Computations for the Nautical Almanac and for much of the American Ephemeris were quickly transferred to the punched card machines, the most time-saving being the subtabulation of the half daily positions of the Moon to an hourly interval.

Now research on the motions of the principal planets, largely neglected since Newcomb's time, seemed more feasible. In addition, much of the drudgery of routine computation was removed by the punched card method. In discussing the observations of Mercury, Dr. Clemence had the help of three Works Progress Administration workers and it required all of their time from January 1940 through February 1942 to form the 57000 coefficients for the equations of condition. He formed the normal equations on the punched card machines, and accomplished in a few days a task that a skilled computer could not have done in three months time. Reduction of transit circle observations was done by hand on large forms with all entries being finally totalled on a manual adding machine. Transfer to the punched card method was accelerated by an incident on a hot August day in the late-forties when a colleague, who had operated the adding machine all day and had amassed an imposing pile of paper tape on the desk, reached over and turned on a high-speed fan. The result; instant confetti. Following the example of the transit instruments, the reduction of other USNO astrometric observations, visual and photographic, as well as the formation of star catalogs were transferred to the punched card machines.

With the end of hostilities, Dr. Eckert returned to New York to become Director of Pure Science at IBM. Dr. Herget became Director of the Cincinnati Observatory and set up a punched card computing laboratory which ultimately became the IAU Minor Planet Center. In 1948 Dr. Brouwer established a similar computing laboratory in the Astronomy Department at Yale University. These organizations cooperated with the Nautical Almanac Office during the late forties and early fifties, in applying their computing facilities to numerous aspects of dynamical astronomy, as attested by titles in the Astronomical Papers of the American Ephemeris such as; "First Order Theory of Mars," "Rectangular Coordinates of Ceres, Pallas, Juno and Vesta, 1920-1960," "The Motion of Jupiter's Fifth Satellite, 1892-1949," "The Secular Variations of the Orbital Elements of the Principal Planets," and "Solar Coordinates 1800-2000," for example.

Although punched card machines continued to supply computing capability well into the fifties, a quiet revolution had been taking place in sequential computing technology, starting with the Harvard Automatic Sequence Controlled Calculator in 1944. The use of vacuum tubes and relay networking then led to the development of several large sequentially operated relay calculators at Harvard University, Bell Labs and IBM. The first electronic sequence controlled calculator (ENIAC) was built at the University of Pennsylvania in 1946. It contained 20,000 vacuum tubes and was designed to compute ballistic trajectories faster than the projectile moved, but the storage capacity and program capability were restricted. When Dr. Eckert returned to IBM in 1946 the company had under construction a new Selective Sequence Electronic Calculator (SSEC) [7]. Dr. Eckert described the speed and mathematical capability of the SSEC in these terms: "With a little practice the average person could multiply two 14-digit numbers together to give a 28-digit answer in about 20 minutes; the machine does 50 such multiplications in a second, or 60,000 in twenty minutes. If the machine should make an error in an 8-hour day this would be only one error in over a million multiplications - less than one per lifetime for a computer with pencil and paper." This high speed, coupled with adequate storage, made the SSEC ideal for solution of a massive problem in dynamical astronomy that had hitherto proven intractable. So, at its inauguration in 1948, the demonstration problem was the simultaneous integration of the equations of motion of the five outer planets from 1653 to 2060.

The next astronomical problem for the SSEC was occasioned by the proposal in 1948 for a new time scale (Ephemeris time), defined by Newcomb's Tables of the Sun. It involved the Moon again. Brown's Theory of the Moon, with appropriate corrections to the longitude to make the independent argument of the lunar ephemeris conform with that of the solar tables, was evaluated for a period of 20 years (1952 - 1972). Observations compared to this Improved Lunar Ephemeris could then be used to derive ET - UT. The harmonic synthesis of over 1400 terms in Brown's Theory proceeded quickly and a comparison with positions derived from the Tables showed small but significant errors both accidental and systematic in the Tables. Other machines quickly followed. Cambridge University in England produced the Edsac in 1949 and in the next few years there appeared the Burroughs E102, the Monroe Monrobot, the RCA Bizmac, the Remington Rand Univac, the IBM 650 and 700 series, and others. Dr. Eckert estimated that in this period there were over thirty groups world wide developing electronic calculators.

In the field of scientific computation, the Age of Camelot began in 1954 when IBM completed the Naval Ordnance Research Calculator (NORC) [8]. In standard computations involving addition, subtraction, multiplication and division with 13-digit numbers the NORC produced 15,000 results in a second. It was straightforward to program and check, and easy to use. Herget quickly transferred all of the numerical integration of minor planet orbits to the NORC and this could be performed in a few runs per year. Both the SSEC and the NORC were decimal machines using four flip-flop elements representing 1, 2, 4, 8 taken one, two or three at a time to give all digits from zero to nine. To the astronomers and other scientists the decimal system was the way God intended man to reckon. To Dr. Herget, who prided himself on writing programs in machine language, this decimal feature was especially important. Within those four flip-flop elements, however, there remained combinations to represent six more counts. The IBM engineers felt the decimal feature was an extravagant waste of hardware and proposed using binary arithmetic only henceforth. To Dr. Herget this suggestion was blasphemous and he muttered that the engineer's paychecks should be made out in binary for a few months until they changed their minds. But efficiency and economy prevailed and when Dr. Herget later worked with an IBM 704 on Project Vanguard, he contented himself with detailing the orbit computation methods to be used and left the coding to others [Fig.4].
When the NORC was introduced in 1954, Dr. Eckert estimated that there were several thousand electronic calculators in operation, with the preponderance being in the U.S.A. In the years preceding and immediately following World War II, however, punched card data processing and electronic calculating techniques were introduced in the national ephemeris offices of many countries.

At the Astronomisches Recheninstitut (ARI) in Berlin, J. Peters began a cooperative program with L. J. Comrie in 1930 to prepare tables of natural trigonometrical functions for every second of arc [9]. In 1935, Peters detailed a conversion from rectangular to spherical coordinates, useful in astrometric plate reductions, using equipment at the Hollerith factory only a few hundred meters from the ARI (Berlin) [11]. In 1955, the Astronomisches Recheninstitut (ARI) in Berlin, used a paper tape controlled drum calculator designated G2 which was developed by a technical group founded by Prof. L.

Bierman of Max-Planck-Institut, Gottingen, for the solution of a problem in dynamical astronomy [1,2]. Dr. Peter Stumpff, then a student of Bierman, was requested by an ARI astronomer to compute the perturbed heliocentric orbit of minor planet Amor on G2. To simplify the task, Stumpff used unperturbed Keplerian ellipses for the perturbing planets (Venus through Saturn). The ARI astronomer refused to accept the G2 results and proceeded to compute the perturbed orbit by hand, using data from the the volume "Planetary Coordinates" for the perturbing planets. When Amor was finally detected the right ascension O-Cs compared to the ARI astronomers orbit were about 2 minutes. Bierman asked Stumpff to compute geocentric positions based on the G2 heliocentric orbit and the O-Cs were only 10 seconds.
At the Astronomisches Recheninstitut in Heidelberg, standard punched card equipment was in use, augmented in 1958 by an IBM626 computer used in the preparation of the annual volume "Apparent Places of Fundamental Stars" from 1960 on. In 1959, ARI personnel used an IBM650 at Darmstadt to compute apparent places for the polar stars of the FK4.

At the Bureau des Longitudes in Paris the subject of computer technology was first raised in 1956 when IBM offered courses in the use of the IBM650, but it was not until the early sixties that application to problems in dynamical astronomy occurred.

In Japan, the Hydrographic Office began using a FACOM 128 Relay Calculator [12] in the compilation of ephemerides as early as 1955.

In the USSR, at the time of the 1958 IAU meeting, delegates were shown a large scale, magnetic tape controlled calculator, similar to an IBM 700 series machine as well as several smaller calculators, but no applications had been made at that time to problems in dynamical astronomy.

At H.M. Nautical Almanac Office, preparation of ephemerides and astronomical tables continued in the late forties and early fifties by punched card methods, augmented in the late fifties by use of an HEC 1201 Calculator.

The U.S. Nautical Almanac Office continued the use of electric punched card machines initiated by Dr. Eckert, slowly upgrading the equipment. By 1955, NAO personnel had access to an IBM650 at the Naval Ordnance Laboratory, and in July 1957 acquired their own.

The growth of computing power, reliability and speed from prior to the punched card era to the large scale calculators of the late fifties caused a revolution in the field of dynamical astronomy. Problems which could not have been attacked by manual computation became tractable. The systematic accuracy of the computations improved, although the perils of programming errors remained to haunt the careless. But best of all, this was the beginning of the age of opportunity for the dynamical astronomer to assault those problems previously considered beyond calculability with freedom from the mind-numbing, tedious drudgery of manual computation. For much of this progress, which saw the transition from the manual evaluation of Brown's Tables to numerical integration of the equations of motion, we can truthfully say "Blame it on the Moon."

REFERENCES.

[1] Annual Report for 1955, Astron. Recheninstitut (Berlin), Mitt. d. Astron. Gesellschaft 1956, p. 59.

[2] Annual Report for 1956, Astron. Recheninstitut (Berlin), Mitt. d. Astron. Gesellschaft 1957, p. 96.

[3] Comrie, L. J. (1928) "On the Construction of Tables by Interpolation," M.N.R.A.S. Vol. 88, pp. 506-523.

[4] Comrie, L. J. (1932) "The Application of the Hollerith Tabulating Machine to Brown's Tables of the Moon," M.N.R.A.S. Vol. 92, pp. 694-707.

[5] Duncombe, R. (1979) "Punched Card Data Processing" in J. Belzer, A. G. Holzman and A. Kent (eds.), Encyclopedia of Computer Science and Technology, Marcal Dekker Inc., New York, N.Y.

[6] Eckert, W. J. (1940), Punched Card Methods in Scientific Computation, Lancaster Press, Lancaster, Pa.

[7] Eckert, W. J. (1948), "Electrons and Computation," The Scientific Monthly, Vol. 67, No. 5.

[8] Eckert, W. J. (1955), Faster, Faster. McGraw-Hill Book Co., New York, N.Y.

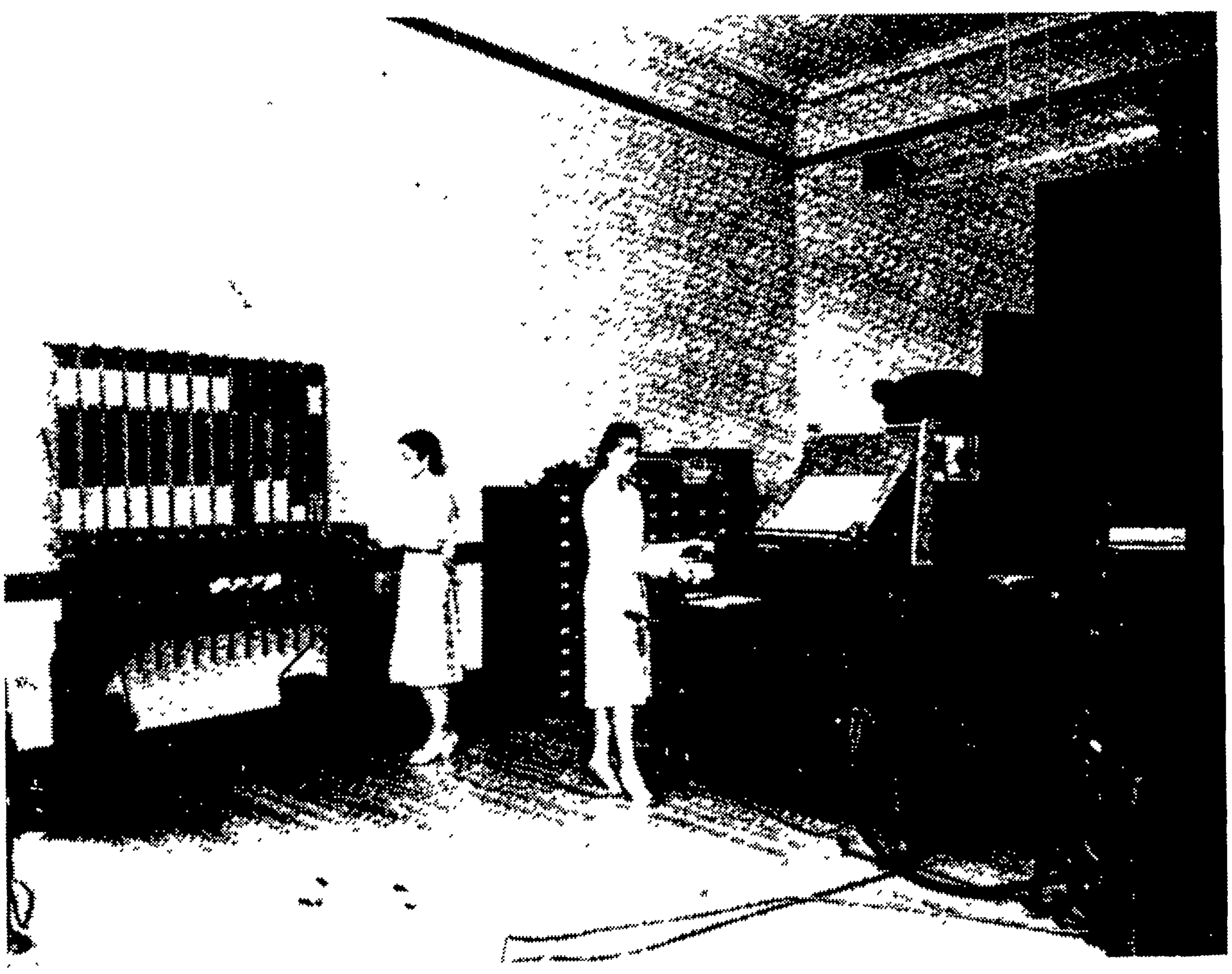
[9] Greaves, W. M. H. (1953) "Obituary of Leslie John Comrie," M.N.R.A.S. Vol. 113, pp. 294-304.

[10] Miller, J. C. P. (1951) "Obituary of Dr. L. J. Comrie," Nature, Vol. 167, pp. 14-15.

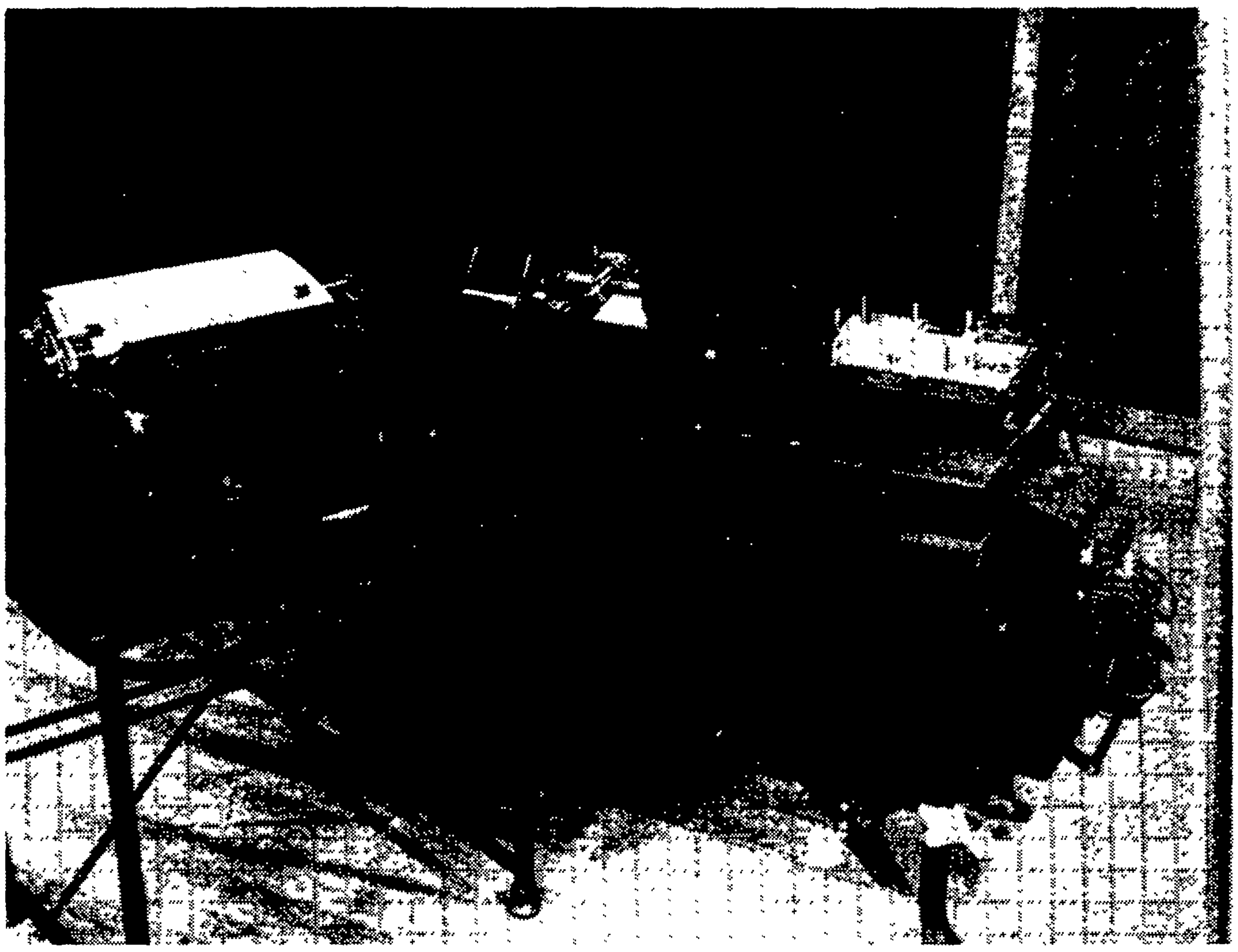
[11] Peters, J. (1935) "Verwendung der Hollerith-Lochkartenmaschinen bei Umwandlung von Tangentialkoordinaten in spharische Koordinaten," Vierteljahrschrift der Astronomischen Gesellschaft, 70 Jahrgang, 4 Heft.

[12] Tsukamoto, Y. (1957) "Ephemerides by Relay Computer," The Astronomical Herald, Japan Astronomical Soc. Vol.6, pp.89-93.

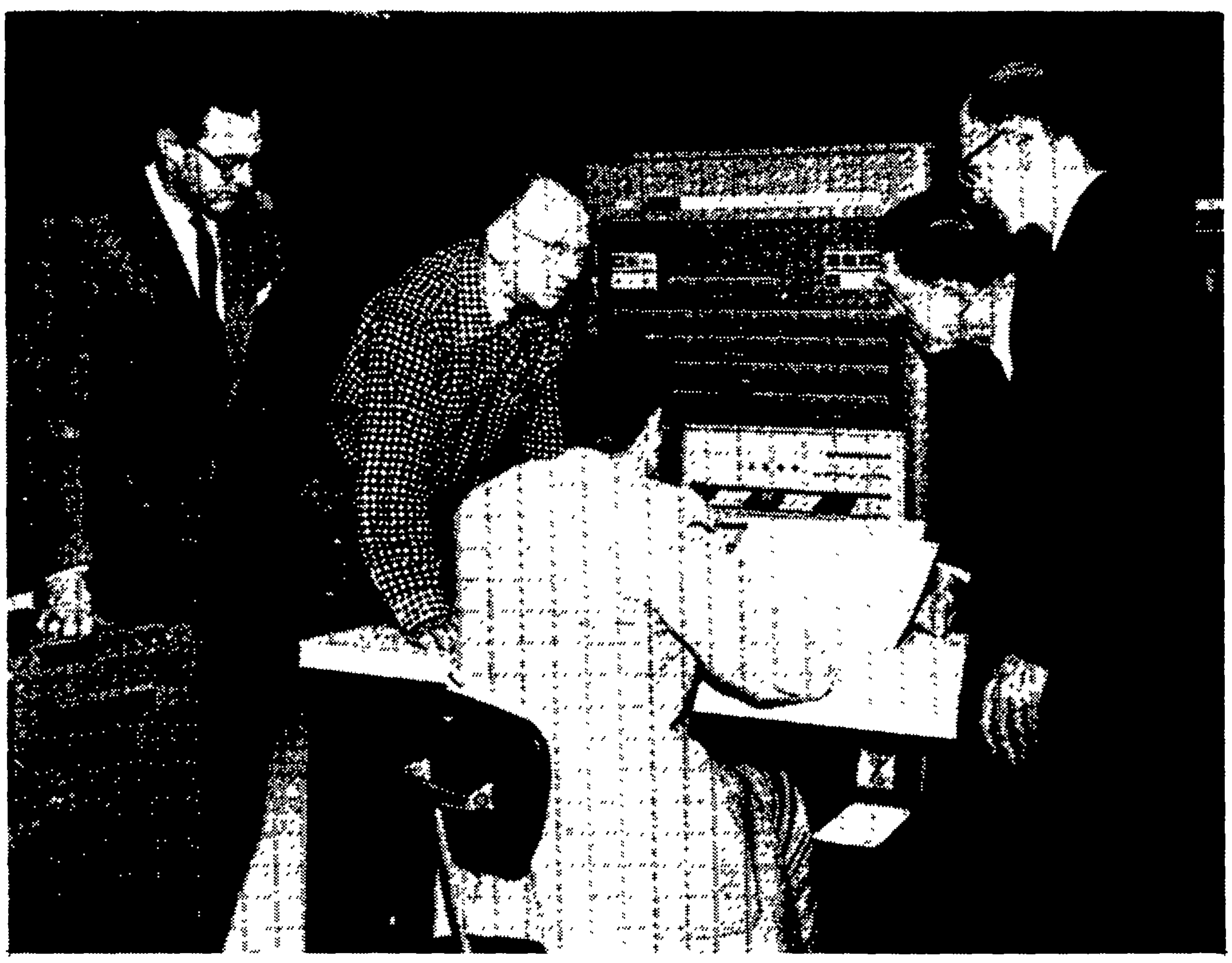
(Fig. 1) Wallace J. Eckert at the time he was Director of the Nautical Almanac Office (1940-1945).



(Fig. 2) Punched Card Computing Laboratory, U. S. Naval Observatory about 1941, showing stand atop tabulator used to support large printers copy forms for the early Air Almanacs.



(Fig. 3) Card operated typewriter, designed by Eckert for Air Almanac printers copy production (1945).



(Fig. 4) Project Vanguard IBM 704. Standing, left to right: Joseph Siry, Paul Herget, Gerald Clemence and Hugh Chrisman.