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# DIGITAL COMPUTER CONTROL OF A RADIO TELESCOPE FOR TRACKING THE SUN, MOON, AND PLANETS

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## ABSTRACT

Altitude-azimuth mounts, which are often employed on radio telescopes because of their mechanical simplicity, complicate the problem of tracking an astronomical body. Even the fixed stars require nonlinear tracking motions on such a mount, while nearer objects require still more complicated motions. A system has been conceived which, by employing a digital computer and a digital servo, is capable of properly controlling an altitude-azimuth mount. It has been demonstrated that a comparatively small digital computer is adequate for off-line operation by programming such a computer to produce tracking coordinates at 6-sec data-sampling intervals. Studies are currently being conducted on the theory of a suitable digital servo.

## PROBLEM STATUS

This is an interim report; work on the problem is continuing.

## AUTHORIZATION

NRL Problem R07-12

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# DIGITAL COMPUTER CONTROL OF A RADIO TELESCOPE FOR TRACKING THE SUN, MOON, AND PLANETS

## INTRODUCTION

The majority of astronomical telescopes employ some form of equatorial mounting. Since the declination of a star is constant and its local hour angle varies at a constant rate, the tracking of a star with an equatorially mounted telescope requires only a constant motion on one telescope axis. For mechanical reasons, large radio telescopes are seldom equatorially mounted. It is generally considered that the altitude-azimuth mounting system is mechanically simpler and economically more feasible. However, this mounting introduces tracking complications. If the astronomical body passes through the zenith, impossible azimuthal tracking rates are required. Even if the latitude of the site is not equal to the declination of the body, assuring that the body will not pass through the zenith, both the azimuthal and altitudinal motions required for tracking will vary with position.

A device to convert the motion of a body into azimuthal and altitudinal rates is usually called an axis converter. Such devices are essentially analog computers, where the analog may be either electrical or mechanical. Unfortunately, it is difficult to obtain an accuracy in an electrical analog computer comparable to the resolution of a large radio telescope. Furthermore, although mechanical analog computers are available which can usually supply the required accuracy, they tend to be inflexible and have limited usefulness for tracking the sun, moon, and planets, whose motions are less regular than a star's. An apparent solution to the problem is to use a digital computer as an axis converter and to produce as its output information that forms a suitable input for a digital servo system. One phase of this investigation has been to demonstrate the feasibility of using a small general-purpose digital computer to control an altitude-azimuth mounted radio telescope.

## GENERAL CONSIDERATIONS

Attention in this study has been confined primarily to tracking the moon, since the moon has the most irregular apparent motion of all astronomical bodies. Any system that will successfully track the moon should track any other astronomical body in the same range of declinations.

The elements necessary to establish the desired tracking motions may be enumerated as follows. (The connections between these elements are shown in Fig. 1.)

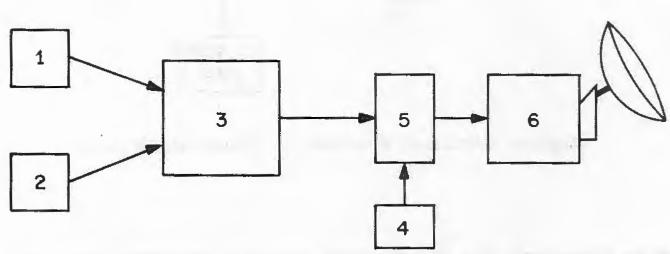


Fig. 1 - Tracking elements

1. Knowledge of the relative motions of the moon and the earth as expressed in the usual ephemeral data as a function of time.

2. Knowledge of the location of the telescope site.

3. A device to determine from elements 1 and 2 the altitude and azimuth of the moon for a given time.

4. A knowledge of time.

5. A device to transfer the output of element 3 at the proper time to element 6.

6. A device to point the telescope to the current position of the moon.

The precise nature of these elements depends on whether or not the computer operates in real time. If it does, elements three and five constitute the computer, and element four is a clock which instructs the computer to gather the necessary input data and transfer the answers to element six. Although this may be the simplest method in concept, its execution requires a fairly fast computer which must always be attached to the system. If the necessity of real-time operation is eliminated by providing a long-term storage capability between elements three and five, the computer can consist of only element three and can be made considerably simpler. This scheme is shown in Fig. 2, in which the storage is on punched paper tape. The computer output tape contains a series of groups, each of which consist of a time code and the altitude and azimuth of the body at this time. The tape can be precomputed in advance for any time interval by any computer. When the tape is placed on the tape reader, the time servo compares the time punched on the tape with the time on the clock and properly advances the tape so that the reader transfers the desired altitude and azimuth to the digital servo at the proper time.

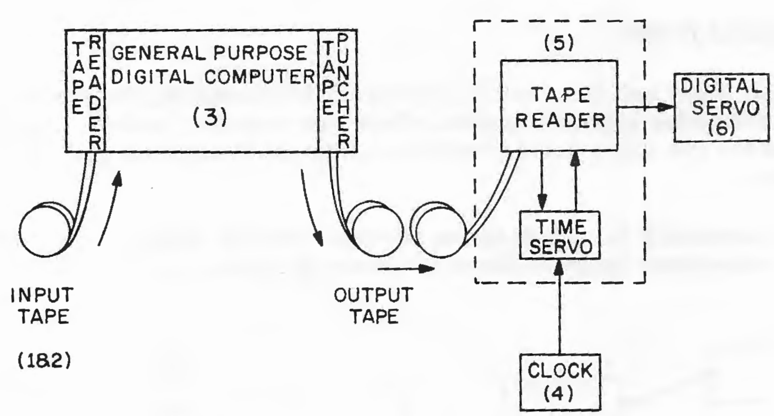


Fig. 2 - Digital control system — block diagram

If the above scheme is adopted, the problem logically divides into two tasks: to select and program a digital computer, and to develop a reader-servo system that will position the telescope in accordance with the computer output tape. The remainder of this report will be concerned primarily with the first task.

## SELECTION AND PROGRAMMING OF THE DIGITAL COMPUTER

### General Considerations

Although a suitable program could be written for almost any general-purpose digital computer, it was thought desirable to utilize the simplest computer capable of producing ouput data at a rate greater than that at which the data is used in tracking. This rate is determined by the number of bits per sample and the sampling interval. It was decided to make 19 bits available for both the altitude and azimuth signals to the servo. This figure corresponds to the capacity of many analog-digital converters and to a precision of 3 sec of arc. A 6-sec sampling interval has been selected. The precision yielded by this interval is dependent on the sophistication of the servo system. If the servo supplies no smoothing at all, a 3-sec time displacement at a tracking rate of 15 degrees per hour corresponds to an error of 45 sec of arc. At high altitudes the azimuthal tracking rate is considerably greater in units of azimuth per unit of time, but the actual error due to a unit error in azimuth is considerably smaller. It is expected that a servo system could provide considerable smoothing and improved system accuracy.

The input data required by the computer consists of the geographical coordinates of the site, a measure of the oblateness of the earth at the site, and tabulations of the Greenwich hour angle (GHA), declination, and horizontal parallax of the moon. Although tabulations of the GHA to an accuracy commensurate with the precision of the other system components and data are not generally available, tabulations of the right ascension of the moon and sidereal time are available to higher accuracy and yield the required data.

The output for each sampling interval consists of 15 hexadecimal characters and format control. The first five characters represent time in hexadecimally coded decimal — two for hours, two for minutes, and one for tenths of minutes. The next five characters are true hexadecimals, the last nineteen bits of which represent the altitude. The last five characters similarly represent azimuth. The format control consists of a character to stop the reader and a character to execute a carriage return if a Flexowriter is used as the reader.

### The LGP-30 Digital Computer

After a survey of commercially available general-purpose digital computers, it was decided that the LGP-30 was one of the simplest computers capable of handling the problem. This device, manufactured by Librascope and distributed by the Royal-McBee Corporation, is in the "under-$50,000" class. It is a fixed-point machine with a 4096-word drum memory and no fast-access memory. There are 16 instructions in the order code. Multiplication and division times are of the order of 19 and 36 milliseconds for optimally and nonoptimally located operands, respectively. Most other arithmetical operations require about 2 and 19 milliseconds for optimal and nonoptimal locations, respectively. Less than 10 percent of the storage locations are optimal for a given instruction location.

A Flexowriter operating at a nominal speed of 10 characters/sec is the normal input-output device. A 200-character/sec photoelectric reader and a 20-character/sec mechanical punch are also available. One limitation of this machine is that it contains no printing or output-buffering registers. Thus the computer itself must be used to synthesize the punching signals, and other computations cease during this interval. With the Flexowriter as the output unit, it is possible to perform about eight typewriter functions per second. The use of the mechanical punch allows the punching of nearly 18 characters/sec.

## Details of Computation

A separate input tape is prepared for each day. Each tape consists of 32 groups of 13 words each. Each group contains the data for a single hour. The 32 groups cover the 24-hour day and 4 hours of the previous and following days. An example of the information in each group is shown in Fig. 3. At present, this information is manually punched on the input tape, but it is also available on punched cards from the Naval Observatory. It should be possible to prepare the input tapes automatically with a card-to-tape converter.

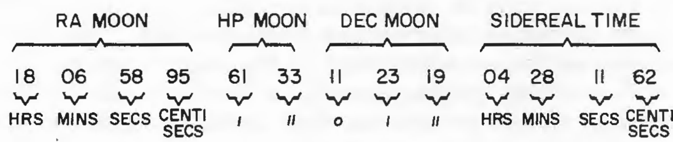


Fig. 3 - Standard input group

After the input tape is read, each of the groups is compressed into four words: RA (right ascension), HP (horizontal parallax), $\delta$ (declination), and ST (sidereal time), expressed in degrees. At this time the computer calls for site data. The site latitude, longitude, and earth oblateness are entered on the keyboard. The local hour angle (LHA) is then computed according to the equation

$$\text{LHA (Modulo 360 degrees)} = \text{ST} - \text{RA} - \text{Longitude.}$$

Subsequently, some of the LHA's are converted to nonprincipal quadrants so that the values will monotonically increase over the 32-hour period.

The computer then requests a selection of a 1-hour interval. This selection is made by typing the proper code words onto the keyboard. The LHA, HP, and $\delta$ are then interpolated to 2-min intervals for the selected 1-hour interval and for the preceding and following intervals. A fourth-central-difference Bessel interpolation method is employed. Computations of altitude and azimuth are then carried out for the 2-min intervals within the desired 1-hour interval and for two corresponding intervals immediately preceding and following the 1-hour interval, according to the equations

$$\text{Alt} = \sin^{-1}\left[\frac{\sin \text{Alt}_{ec} - \epsilon \sin \text{HP}}{\left[1 - 2\,\epsilon \sin \text{HP} \sin \text{Alt}_{ec} + (\epsilon \sin \text{HP})^2\right]^{1/2}}\right]$$

where $\epsilon$ = eccentricity

and $\sin \text{Alt}_{ec} = \sin \text{Lat} \sin \delta + \cos \text{Lat} \cos \delta \cos \text{LHA}$,

and

$$\text{Az} = \tan^{-1}\left[\frac{\sin \text{LHA}}{\cos \text{LHA} \sin \text{Lat} - \tan \delta \cos \text{Lat}}\right]$$

where $\delta$ = declination.

| HOUR | MIN | ALT | AZIMUTH |
|---|---|---|---|
| 14 | 56 | -005.19161 | 064.90076 |
| 14 | 58 | -004.84437 | 065.20804 |
| 15 | 00 | -004.49624 | 065.51421 |
| 15 | 02 | -004.14722 | 065.81927 |
| 15 | 04 | -003.79733 | 066.12323 |
| 15 | 06 | -003.44661 | 066.42616 |
| 15 | 08 | -003.09505 | 066.72806 |
| 15 | 10 | -002.74267 | 067.02895 |
| 15 | 12 | -002.38948 | 067.32888 |
| 15 | 14 | -002.03550 | 067.62783 |
| 15 | 16 | -001.68074 | 067.92585 |
| 15 | 18 | -001.32520 | 068.22297 |
| 15 | 20 | -000.96891 | 068.51916 |
| 15 | 22 | -000.61187 | 068.81450 |
| 15 | 24 | -000.25409 | 069.10898 |
| 15 | 26 | 000.10442 | 069.40262 |
| 15 | 28 | 000.46364 | 069.69546 |
| 15 | 30 | 000.82356 | 069.98750 |
| 15 | 32 | 001.18418 | 070.27879 |
| 15 | 34 | 001.54547 | 070.56933 |
| 15 | 36 | 001.90744 | 070.85912 |
| 15 | 38 | 002.27006 | 071.14823 |
| 15 | 40 | 002.63334 | 071.43664 |
| 15 | 42 | 002.99725 | 071.72440 |
| 15 | 44 | 003.36179 | 072.01152 |
| 15 | 46 | 003.72695 | 072.29803 |
| 15 | 48 | 004.09272 | 072.58395 |
| 15 | 50 | 004.45909 | 072.86926 |
| 15 | 52 | 004.82604 | 073.15406 |
| 15 | 54 | 005.19357 | 073.43828 |
| 15 | 56 | 005.56167 | 073.72203 |
| 15 | 58 | 005.93032 | 074.00527 |
| 16 | 00 | 006.29953 | 074.28805 |
| 16 | 02 | 006.66924 | 074.57042 |
| 16 | 04 | 007.03948 | 074.85239 |

Fig. 4 - Hourly Summary Sheet

| |
|---|
| 152470000229gl' |
| 152480000229jw' |
| 152490000229qq' |
| 15250000022f0j' |
| 15251000022f2f' |
| 15252000022f48' |
| 15253000022f66' |
| 15254000022f84' |
| 152550001q22ff2' |
| 152560004222fj0' |
| 152570006722fkq' |
| 152580008j22fwj' |
| 15259000gl22glf' |
| 15260000k522g38' |
| 15261000wf22g56' |
| 15262001lw22g74' |
| 152630014422g92' |
| 152640016822gg0' |
| 152650018k22gjq' |
| 15266001g222gqj' |
| 15267001k722j0f' |
| 15268001wg22j28' |
| 152690022022j46' |
| 152700024522j64' |
| 152710026f22j82' |
| 152720028w22jf0' |
| 15273002g322jgq' |
| 15274002k822jkj' |
| 15275002wk22jwf' |
| 152760032222k18' |

Fig. 5 - Printout of control tape

Words corresponding to the times for which these computations are made are then synthesized and the results are printed on a summary sheet (Fig. 4).

The central thirty 2-min intervals are further interpolated to 6-sec intervals. Negative altitudes are replaced with zeros, and time groups are synthesized. The computer then punches the output tape. A print-out of a portion of the output tape is shown in Fig. 5.

Figure 6 is a block diagram of the program. It is simply a summary of the processes involved in the program and in no respect constitutes a flow diagram. The complete coding and flow diagrams are given in the Appendix. Table 1 summarizes the operating times for various portions of the program. As can be seen, the program is capable of producing an hour of tracking data in less than an hour.

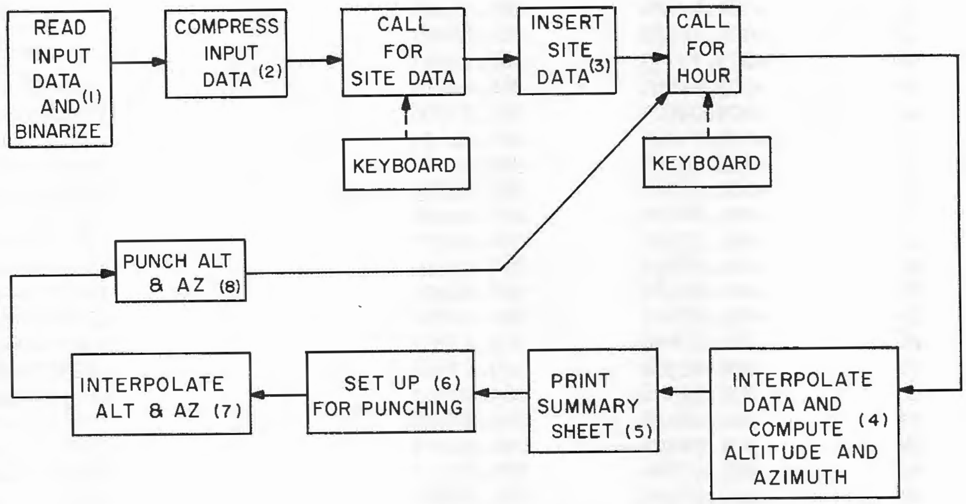


Fig. 6 – Moon track program – block diagram

**TABLE 1**

| OP# (Ref. Fig. 6) | Time | Number of Times/Hour's Data | Time/Hour's Data |
|---|---|---|---|
| 1 | 5:12 | <<1 | - |
| 2 | :48 | <<1 | - |
| 3 | :36 | <<1 | - |
| 4 | 5:18 | 1 | 5:18 |
| 5 | 4:01 | 1 | 4:01 |
| 6 | :41 | 1 | :41 |
| 7 | :23 | 30 | 11:30 |
| Flex → 8A | 1:00 | 30 | 30:00 |
| Fast Punch → 8B | :22 | 30 | 11:00 |
| | Total Time/Hour's Data | | 51:30 (Flex) 32:30 (Fast Punch) |

## CONCLUSIONS

It would appear that an accurate and flexible axis converter for an altitude-azimuth mounted radio telescope would consist of a digital computer and a digital servo reading the output tape of the computer under the control of a clock. It has been demonstrated that even a small general-purpose digital computer is capable of providing control information. A program for tracking the moon, one of the more difficult conversions, can be run on an LGP-30 computer at speeds in excess of real-time requirements. Studies on the theory of a digital servo are now underway, and no unusual difficulties are anticipated.

## ACKNOWLEDGMENTS

The author would like to acknowledge helpful discussions concerning the LGP-30 computer with Eldred J. Haley and Robert E. Terry of the Royal-McBee Corporation.

* * *

# APPENDIX

## Moon Track Program

This appendix presents the coding and flow diagrams for the moon track program. The order code for the LGP-30 computer is given below.

| | |
|---|---|
| a nnnn | Add the contents of nnnn to the contents of the accumulator and place the sum in the accumulator. |
| b nnnn | Bring the contents of nnnn to the accumulator. |
| c nnnn | Place the contents of the accumulator in nnnn and clear the accumulator. |
| d nnnn | Divide the contents of the accumulator by the contents of nnnn and place the quotient in the accumulator. |
| e nnnn | Extract a portion of the contents of the accumulator by performing a Boolean multiplication with the contents of nnnn and place the result in the accumulator. |
| h nnnn | Hold the contents of the accumulator in nnnn while also retaining the contents of the accumulator. |
| i 0000 | Let the output of the Flexowriter feed into the accumulator. |
| m nnnn | Multiply the contents of the accumulator by the contents of nnnn and place the high-order product in the accumulator. |
| n nnnn | Multiply the contents of the accumulator by the contents of nnnn and place the low-order product in the accumulator. |
| p nnnn | Perform the Flexowriter function described by six of the bits of nnnn. |
| r nnnn | Place in the address portion of the word in location nnnn the location of the r order increased by two. |

| | |
|---|---|
| s nnnn | Subtract the contents of nnnn from the contents of the accumulator, placing the difference in the accumulator. |
| t nnnn | Transfer control to nnnn if and only if the quantity in the accumulator is negative. |
| u nnnn | Transfer control to nnnn. |
| y nnnn | Replace the address portion of the word in nnnn with the address portion of the contents of the accumulator. |
| z nnnn | Stop. |

The program utilizes several subroutines. Coding and flow diagrams are given below for the interpolation and punching subroutines. The other subroutines are standard ones available from the Royal-McBee Corporation. Their initial locations are tabulated below.

| SUBROUTINE | INITIAL LOCATION |
|---|---|
| Data Input #3 | 4000 |
| Data Output #2 | 4300 |
| Sine-Cosine | 4600 |
| Arc Tangent | 4700 |
| Alphanumeric | 4800 |
| Arc Sine | 4900 |
| Square Root | 5000 |

Figures A-1a through A-3 are flow diagrams for the main program and for the interpolation and punching subroutines. Figures A-4 through A-7 are copies of the coding for the processes outlined in the flow diagrams.

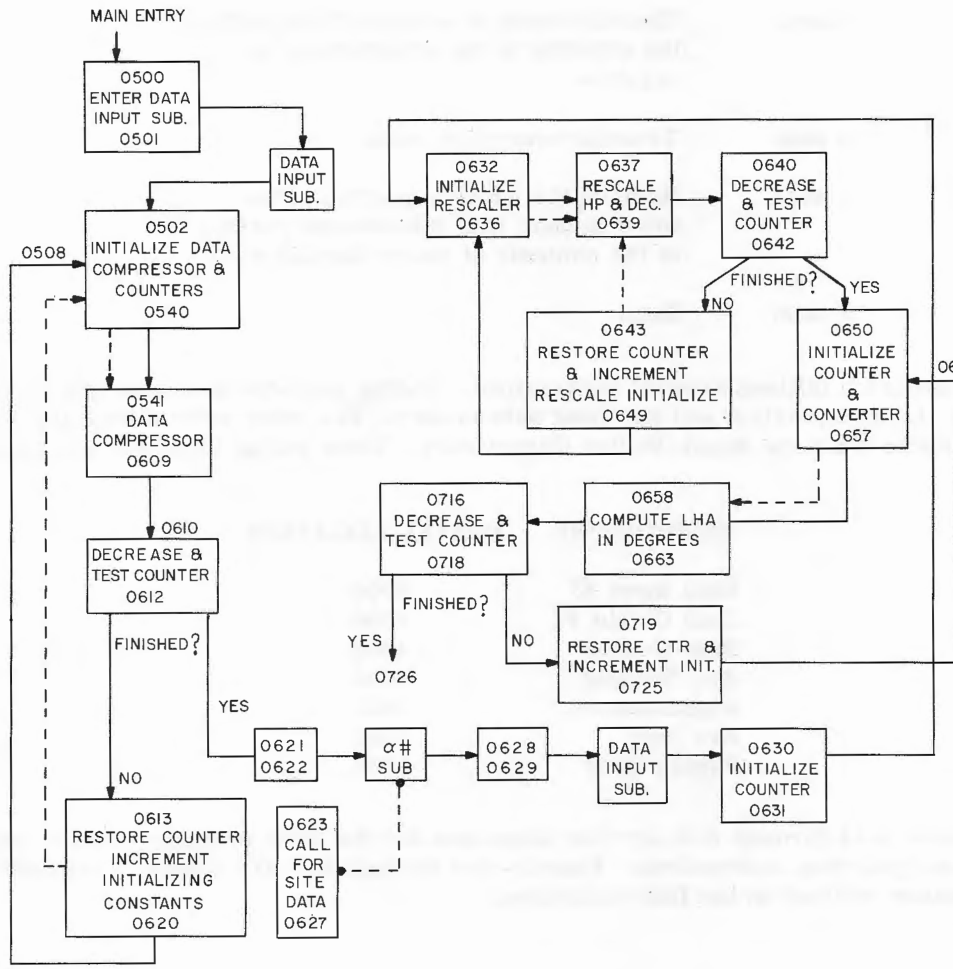


Fig. A-1a — Moon track — flow diagram

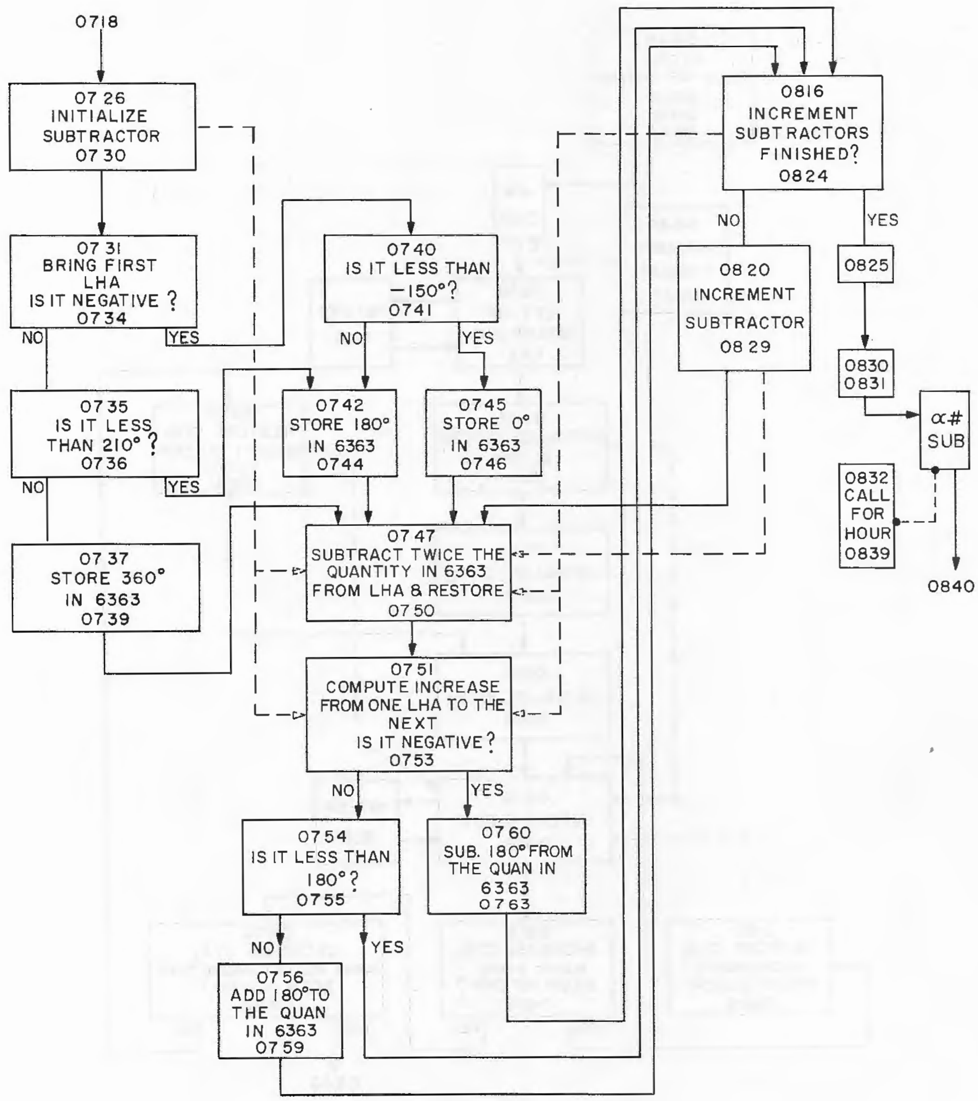


Fig. A-1b — Moon track — flow diagram continued

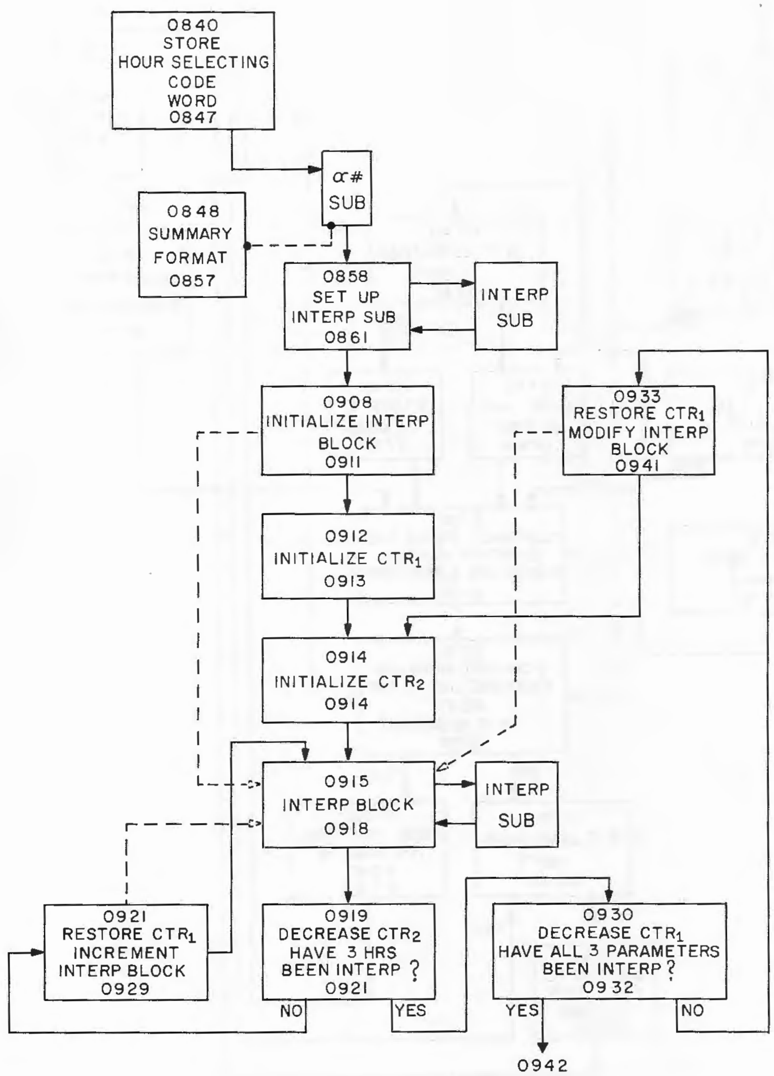


Fig. A-1c — Moon track — flow diagram continued

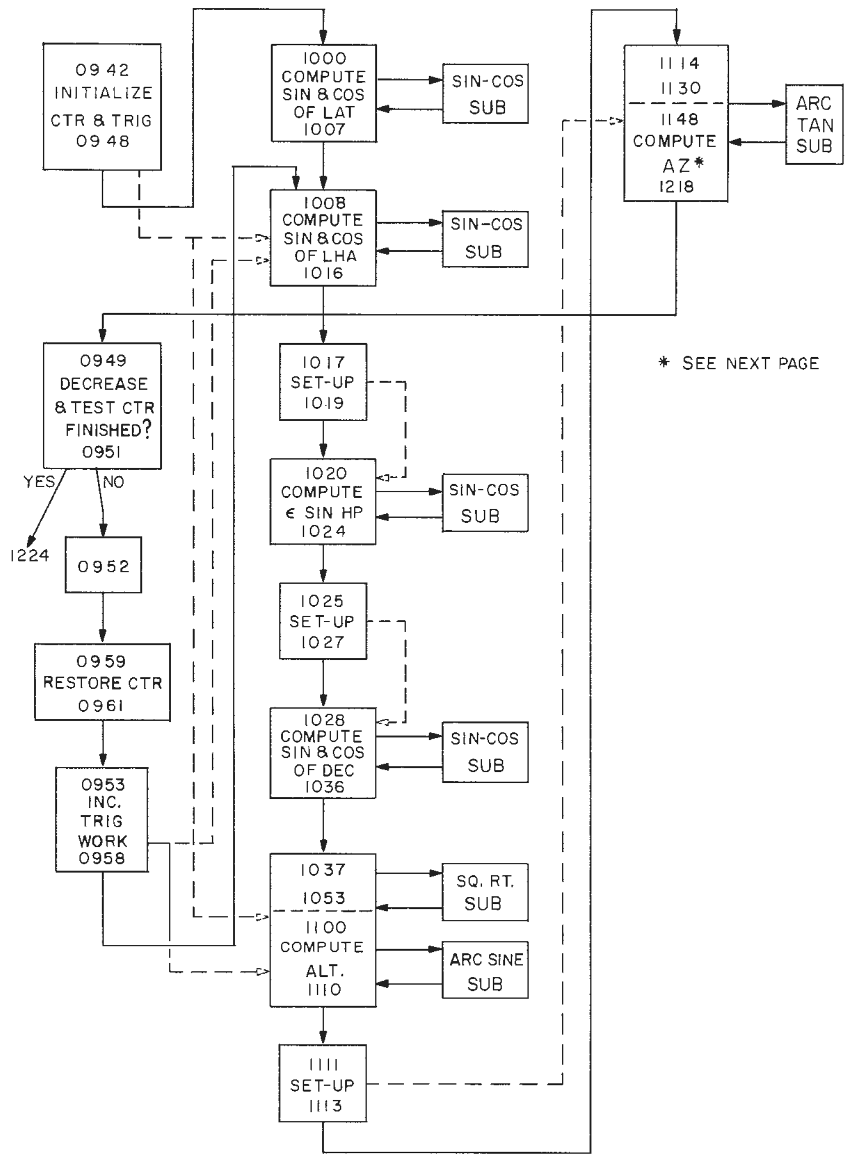


Fig. A-1d — Moon track — flow diagram continued

$$Az = \tan^{-1} \frac{\sin LHA}{\cos LHA \sin Lat - \tan \delta \cos Lat} = \frac{a}{b} \quad \text{where if a is + } 360>Az>180, \text{ if a is - } 180>Az>0$$

we also desire to take $\tan^{-1} x$ where $|x| \leq 1$

| Case | | | | | Const. # | Value |
|---|---|---|---|---|---|---|
| Case 0 | $\lvert a\rvert \leq \lvert b\rvert$ | a is - | b is - | $Az = \tan^{-1} a/b$ | 0 | 0 |
| 1 | $\lvert a\rvert \leq \lvert b\rvert$ | a is - | b is + | $Az = 180° + \tan^{-1} a/b$ | 1 | 180° |
| 2 | $\lvert a\rvert \leq \lvert b\rvert$ | a is + | b is - | $Az = 360° + \tan^{-1} a/b$ | 2 | 360° |
| 3 | $\lvert a\rvert \leq \lvert b\rvert$ | a is + | b is + | $Az = 180° + \tan^{-1} a/b$ | 3 | 180° |
| 4 | $\lvert a\rvert \geq \lvert b\rvert$ | a is - | b is - | $Az = 90° - \tan^{-1} b/a$ | 4 | 90° |
| 5 | $\lvert a\rvert \geq \lvert b\rvert$ | a is - | b is + | $Az = 90° - \tan^{-1} b/a$ | 5 | 90° |
| 6 | $\lvert a\rvert \geq \lvert b\rvert$ | a is + | b is - | $Az = 270° - \tan^{-1} b/a$ | 6 | 270° |
| 7 | $\lvert a\rvert \geq \lvert b\rvert$ | a is + | b is + | $Az = 270° - \tan^{-1} b/a$ | 7 | 270° |

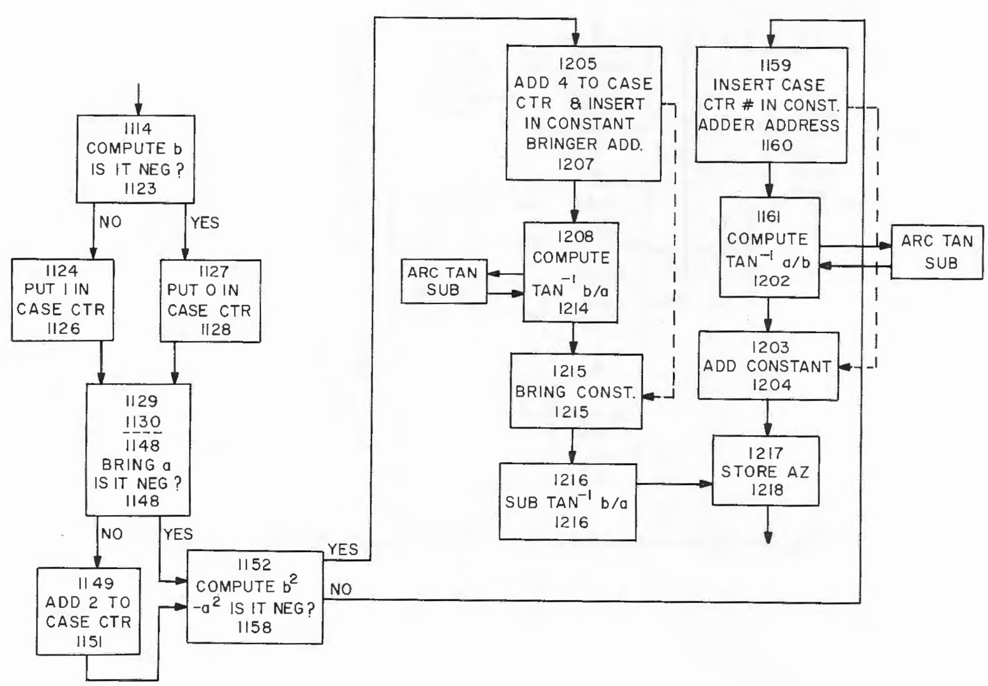


Fig. A-1e — Moon track — flow diagram continued

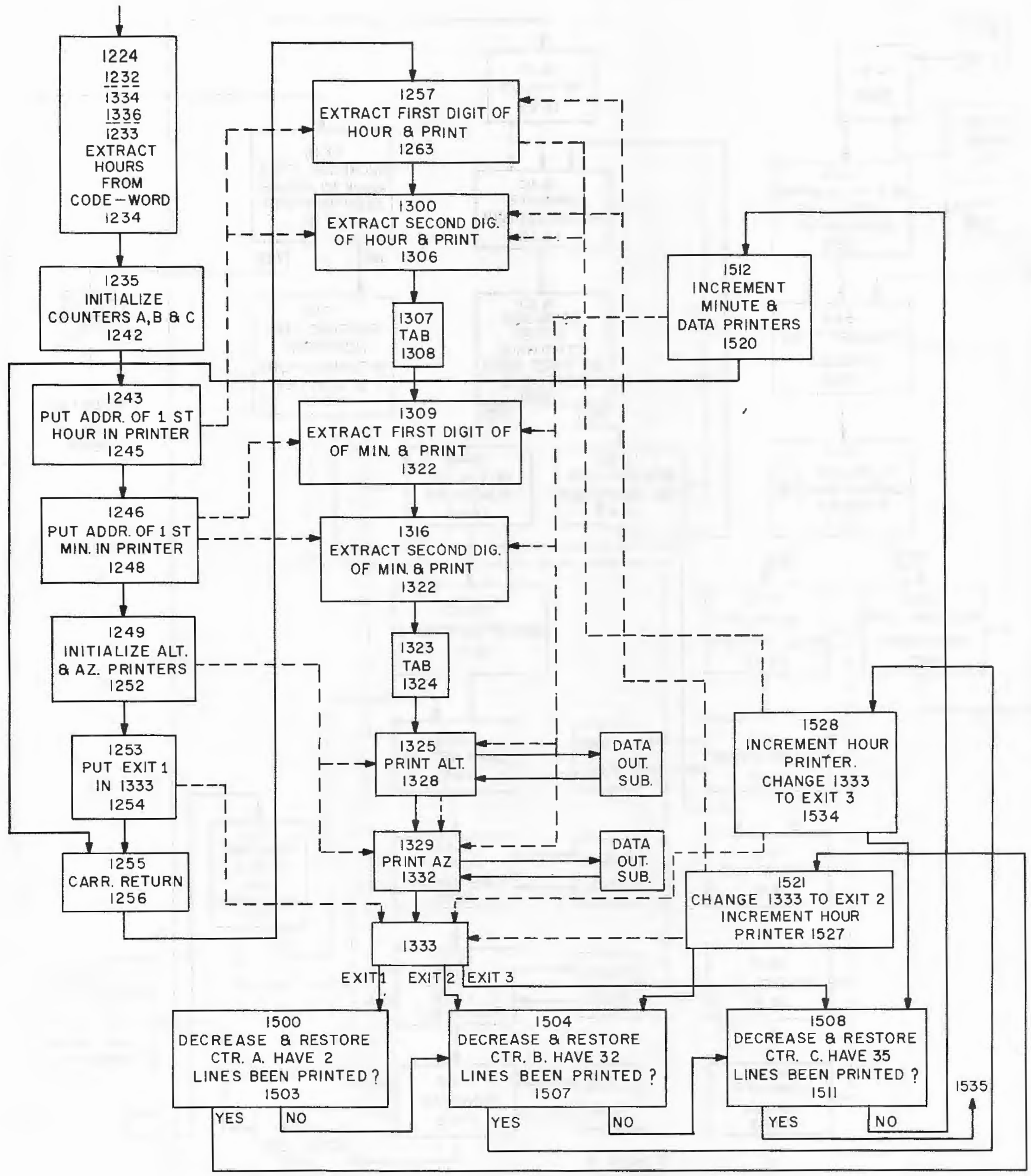


Fig. A-1f — Moon track — flow diagram continued

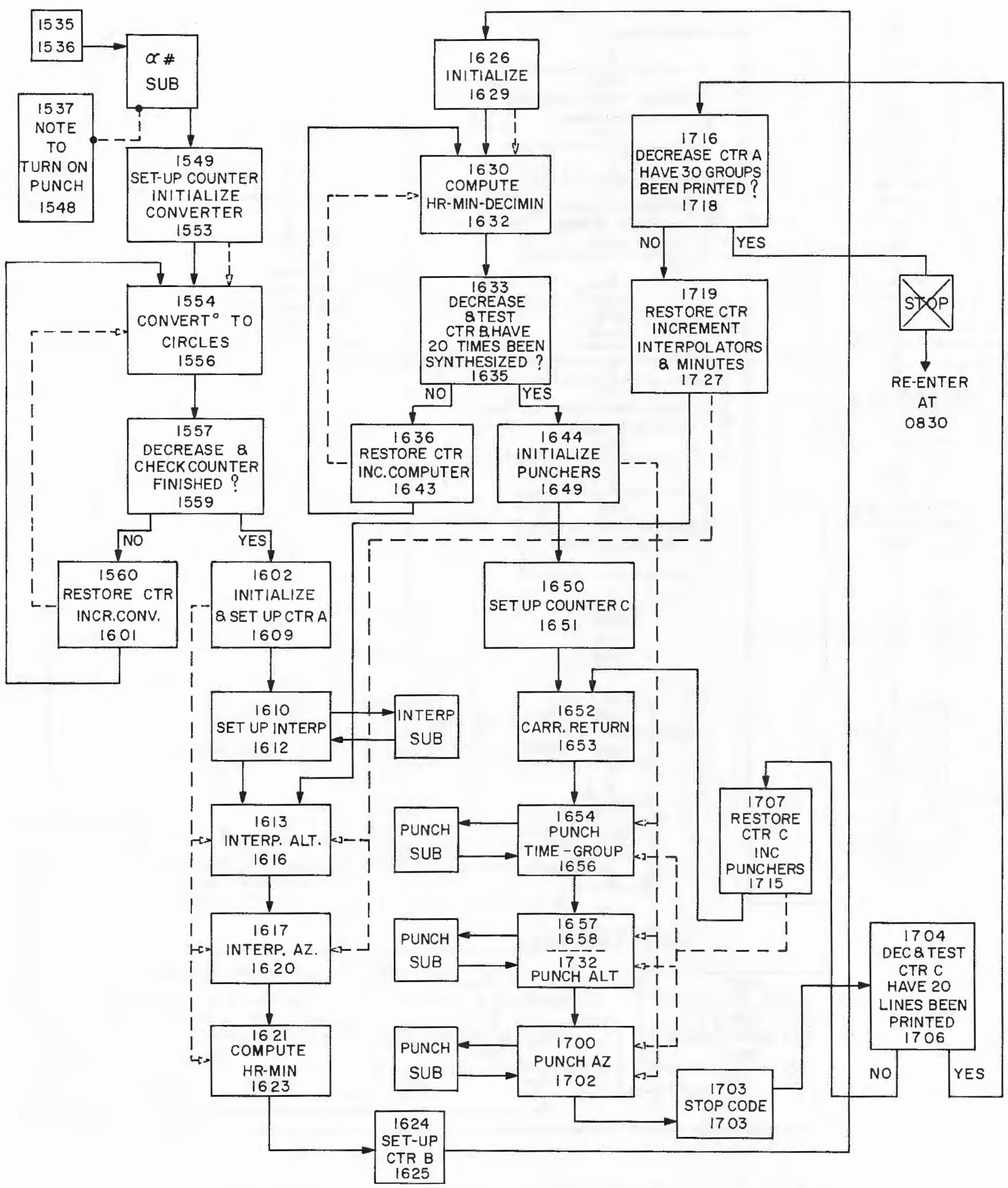


Fig. A-1g — Moon track — flow diagram continued

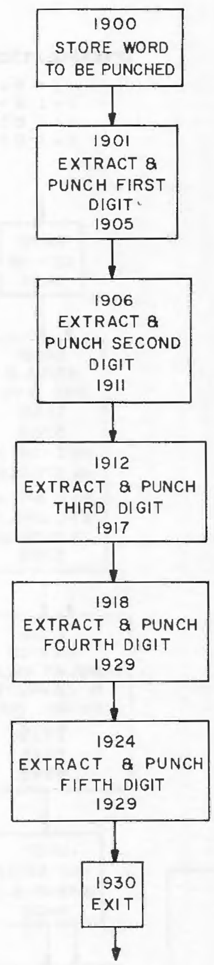


Fig. A-2
Punching subroutine
flow diagram

SET-UP ENTRY

| | |
|---|---|
| $\alpha$ | R 5700 |
| $\alpha + 1$ | U 5600 |
| $\alpha + 2$ | Z 00 $n_1 n_2$ |

where the interval is to be divided into $n_1 n_2$ parts

INTERPOLATION ENTRY

| | |
|---|---|
| $\beta$ | B a |
| $\beta + 1$ | H b |
| $\beta + 2$ | R 5800 |
| $\beta + 3$ | U 5650 |

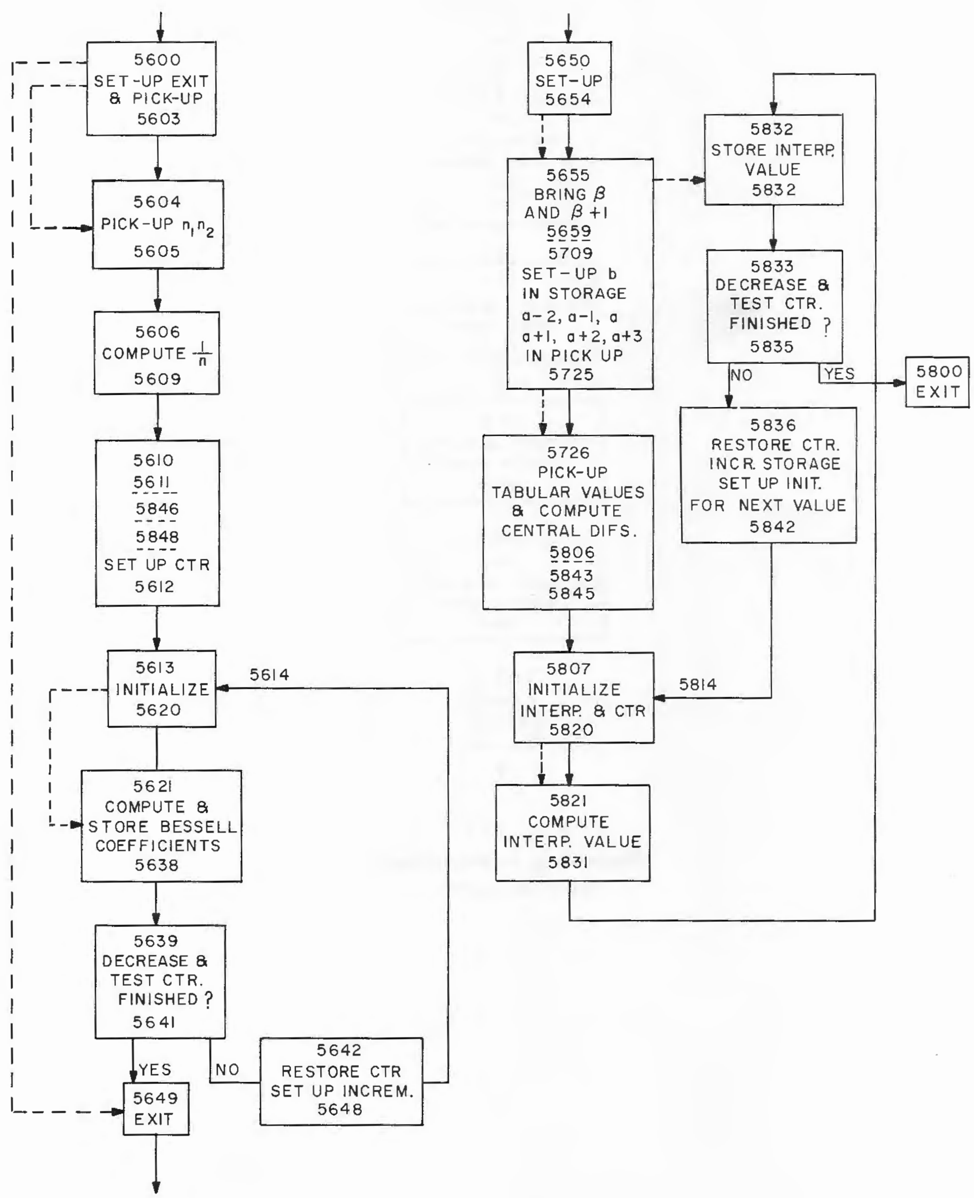


Fig. A-3 — Interpolation subroutine — flow diagram

```
0500 000r4008'u4000'b0700'h6300'b0701'h6301'b0702'h6302'
0508 000b6300'y0548'a0703'y0546'a0703'y0544'a0703'y0542'
0516 000a0703'y0552'a0703'y0550'a0703'y0560'a0703'y0557'
0524 000a0703'y0555'a0703'y0608'a0703'y0606'a0703'y0604'
0532 000a0703'y0602'b6301'y0549'a0704'y0554'a0704'y0601'
0540 000a0704'y0609'b0000'm0800'a0000'm0801'a0000'm0801'
0548 000a0000'h0000'b0000'm0801'a0000'm0801'h0000'b0000'
0556 000m0801'a0000'm0801'h6363'b0000't0600'a6363'u0601'
0600 000s6363'h0000'b0000'm0800'a0000'm0801'a0000'm0801'
0608 000a0000'h0000'b6302's0703't0621'h6302'b0602'a0703'
0616 000h6300'b6301'a0703'h6301'u0508'r4800'u4800'
0623 20087f22'5f4f062f'725f7236'06420j4f'727f4fvq'
0628 000r4008'u4000'b0708'h6300'
0632 000b0701'a0704'y0637'b0709'y0639'b0000'm0802'h0000'
0640 000b6300's0703't0650'h6300'b0637'a0703'y0637'b0639'
0648 000a0703'u0636'b0702'h6300'b0710'y0662'b0701'y0659'
0656 000a0711'y0658'b0000's0000'd0803's0706'h0000'u0716'
0700 000z3000'z2000'z0031'z0001'z0032''''
0708 000z0063'z3532'z3632'z0132'z3500'z6363'z3701'z0002'
0716 000b6300's0703't0726'h6300'b0662'a0703'y0662'b0659'
0724 000a0703'u0655'b0710'y0747'y0752'a0703'y0751'b0712'
0732 000y0750'b3632't0740's0804't0742'b0805'h6363'u0747'
0740 000a0806't0745'b0807'h6363'u0747'c6363'c6363'b0000'
0748 000s6363's6363'h0000'b0000's0000't0760's0807't0816'
0756 000b6363'a0807'h6363'u0816'b6363's0807'h6363'u0816'
0800 0147fq14'02222222'20000000'22222222'
0804 34800000'5f000000'25800000'2k000000'
0808 40000000'00800000'0ww00000'10000000'
0812 000ww000'00100000'00000ww0'00001000'
0816 000b0747'a0703'y0747'y0752'a0703'y0751'e0713's0714'
0824 000t0826'u0830'b0750'a0703'y0750'u0747'r4800'u4800'
0832 20087f4f'0j4f6f5f'062f4f7f'221f4f2f'
0836 06624652'1f062232'066f462f'4f2a20vq'
0840 000p0000'i0000'c0900'p0000'i0000'c0901'r4800'u4800'
0848 20085f62'72326j06'1246522a'20202020'10624652'
0853 1f303f22'3230720j'5f307202'223f525f'620820vq'
0858 000r5700'u5600'z0030'u0908'''''
0902 000z0104'z0034'z2028'z2700'z0200'z0100'
0908 000b0901'y0915'b0701'y0916'b0715'h0862'h0863'b0000'
0916 000h0000'r5800'u5650'b0863's0703't0930'h0863'b0915'
0924 000a0703'y0915'b0916'a0860'y0916'u0915'b0862's0703'
0932 000t0942'h0862'b0915'a0860'y0915'b0916'a0902'y0916'
0940 000b0715'u0914'b0903'h0863'b0904'y1008'b0905'y1110'
0948 000u1000'b0863's0703't1224'u0959'a0703'y1008'b1110'
0956 000a0703'y1110'u1008'h0863'b1008'u0953'''
```

Fig. A-4 — Moon track coding

```
1000 000b0705'r4649'u4600'h1063'b0705'r4649'u4604'h1062'
1008 000b0000'h1060'r4649'u4600'h1061'b1060'r4649'u4604'
1016 000h1060'b1008'a0906'h1020'b0000'r4649'u4600'm0707'
1024 000h1059'b1020'a0906'h1028'b0000'h1057'r4649'u4600'
1032 000h1058'b1057'r4649'u4604'h1057'm1062'm1060'h1056'
1040 000b1058'm1063'u1044'z0000'a1056'a1056'h1055'a1055'
1048 000c1054's1054's1054'a1059'm1059'u1100'

1100 000a0802'r5050'u5000'c1132's1059'm0808'a1055'd1132'
1108 000r4921'u4900'h0000'b1110'a0907'y1217'b1058'd1057'
1116 000m1062'h1132'b1060'm1063'd0808's1132'h1132't1127'
1124 000b1134'h1133'u1129'b1135'h1133'b1061'u1148'z0000'
1132 000z0000'z0000'z1141'z1140'z0000'z0004'z1361'z1400'
1140 00000000'2k000000'5f000000'2k000000'
1144 16800000'16800000'43800000'43800000'
1148 000t1152'b1133'a0715'h1133'b1061'm1061'h1136'b1132'
1156 000m1132's1136't1205'b1133'y1203'b1061'm0808'd1132'
1200 000m0809'r4751'u4700'a0000'u1217'b1133'a1137'y1215'
1208 000b1132'm0808'd1061'm0809'r4751'u4700'h1132'b0000'
1216 000s1132'h0000'u0949''''''
1224 000b0900'e0810'd0811'h1361'b0900'e0812'd0813'h1362'
1232 000u1334'd0815'h1363'b0903'b0903'h1360's0715's0703'
1240 000h1359'b0703'h1358'b1138'y1258'y1301'b1139'y1310'
1248 000y1317'b0905'y1325'a0907'y1329'b1348'y1333'p1600'
1256 000z0000'b1435'e0000'm1436'a1349'h1262'z0000'z0000'
1300 000b1437'e0000'm1438'a1349'h1305'z0000'z0000'p2400'
1308 000z0000'b1439'e0000'm1440'a1349'h1314'z0000'z0000'
1316 000b1441'e0000'm1442'a1349'h1321'z0000'z0000'p2400'
1324 000z0000'b0000'r4305'u4300'z0109'b0000'r4305'u4300'
1332 000z0109'u0000'b0900'e0814'u1233'

1348 000z1500'p0200'z1504'z1508'z2702'z0029'z0019'z1800'

1400 002g0000'2j0000'000000'010000'020000'030000'
1406 00040000'080000'090000'0f0000'0g0000'0j0000'
1412 00100000'110000'120000'130000'140000'180000'
1418 00190000'1f0000'1g0000'1j0000'200000'210000'
1424 00220000'230000'240000'280000'290000'2f0000'
1430 002g0000'2j0000'000000'010000'020000'
1435 78000000'00004000'07800000'00040000'00780000'
1440 00400000'00078000'04000000'5g05g05g'
```

Fig. A-5 — Moon track coding continued

```
1500 000b1358's0703'h1358't1521'b1359's0703'h1359't1528'
1508 000b1360's0703'h1360't1535'b1310'a0703'y1310'y1317'
1516 000a1139'y1329's0907'y1325'u1255'b1350'y1333'b1258'
1524 000a0703'y1258'y1301'u1504'b1258'a0703'y1258'y1301'
1532 000b1351'y1333'u1508'r4800'u4800'
1537 20202020'10187f7j'225f6f62'065f4606'
1541 4252326f'62065f4f'32067f4f'6f46322f'
1545 7f06541f'463f0618'32467j08'202020vq'
1549 000b0905'y1554'y1556'b0906'h6300'b0000'm1443'
1556 000h0000'b6300's0703't1602'h6300'b1554'a0703'y1554'
1600 000y1556'u1554'b1352'y1613'a0907'y1617's1139'y1621'
1608 000b1353'h1356'r5700'u5600'z0020'b0000'h2920'r5800'
1616 000u5650'b0000'h2940'r5800'u5650'b0000'a1362'h1357'
1624 000b1354'h6300'b1355'y1630'b1663'y1632'b0000'a1357'
1632 000h0000'b6300's0703't1644'h6300'b1630'a0703'h1630'
1640 000b1632'a0703'h1632'u1630'b1663'y1654'a1662'y1657'
1648 000a1662'y1700'b1354'h1661'p1631'z0000'b0000'r1930'
1656 000u1900'b0000'u1732'z0000'z0000'z0000'z0020'z2900'
1700 000b0000'r1930'u1900'p3246'b1661's0703't1716'h1661'
1708 000b1654'a0703'y1654'a1662'y1657'a1662'y1700'u1652'
1716 000b1356's0703't1728'h1356'b1613'a0703'y1613'a0907'
1724 000y1617's1139'y1621'u1613'z0000'u0830'''
1732 000t1736'r1930'u1900'u1700'b1958'u1733'

1800 00000000'0800'1000'1800'2000'2800'3000'3800'4000'4800'
1810 00008000'8800'9000'9800'f000'f800'g000'g800'j000'j800'



1900 000h1959'e1937'm1938'a1939'h1905'z0000'b1959'e1943'
1908 000m1944'a1945'h1911'z0000'b1959'e1949'm1950'a1951'
1916 000h1917'z0000'b1959'e1955'm1956'a1957'h1923'z0000'
1924 000b1959'e1961'm1962'a1963'h1929'z0000'u0000'

1937 78000000'00004000'p0241'

1943 07800000'00040000'p0247'

1949 00780000'00400000'p0253'

1955 00078000'04000000'p0259'

1961 00007800'40000000'p0201'
```

Fig. A-6 — Moon track coding continued
and punching subroutine coding

```
0000 000b0100' y0004' a0101' y0049' b0000' h0063' b0101' d0063'
0008 000h0062' h0061' b0063' u0246' h0060' b0102' y0038' a0101'
0016 000y0029' a0101' y0025' a0101' y0022' b0061' h0000' m0103'
0024 000s0103' h0000' b0061' s0103' m0104' h0000' b0061' m0105'
0032 000s0103'xh6300' b0061' m0104' a0104'xm6300' h0000' b0060'
0040 000s0101' t0049' h0060' b0061' a0062' h0061' b0022' a0101'
0048 000u0014' u0000' b0200' s0106' y0057' s0101' y0055' b0000'
0056 000h0107' b0000' h0108' u0109'''''
0100 000z0000'xz0001' z0300'40000000'2fffffff'20000000'xz0003''
0108 000z0000' b0107' a0106' y0126' s0101' y0127' y0129' s0101'
0116 000y0130' y0132' s0101' y0133' y0135' s0101' y0137' y0139'
0124 000s0101' y0140' b0000' s0000'xh6300' b0000' s0000'xh6301'
0132 000b0000' s0000'xh6315' b0000'xh6317' s0000'xh6302' b0000'
0140 000s0000'xh6303'xb6300'xs6301'xh6304'xb6301'xs6315'xh6305'
0148 00xb6315'xs6302'xh6306'xb6302'xs6303'xh6307'xb6304'xs6305'
0156 00xh6308'xb6305'xs6306'xh6360'xb6306'xs6307'xh6309' u0201'
0200 000u0000'xb6308'xs6309'xh6357'xb6305'xa6306' u0243' b0063'
0208 000s0101' h0060' b0108' a0101' y0232' b0102' y0222' a0101'
0216 000y0225' a0101' y0228' a0101' y0230'xb6357' m0000'xh6359'
0224 00xb6360' m0000'xa6359'xa6313' m0000'xa6315' m0000'xa6317'
0232 000h0000' b0060' s0101' t0200' h0060' b0232' a0101' y0232'
0240 000b0230' a0101' u0214' m0103'xh6313' u0207' s0101' s0101'
0248 000u0012'
```

NOTE: When this subroutine is used with the moon-track program, the addresses of all orders not preceded by an "x" are increased by 5600.

Fig. A-7 — Interpolation subroutine