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STRAPDOWN INERTIAL MEASUREMENT UNIT COMPUTER

by

A. James Lincoln, Paul Carpenter, and Robert E. Oleksiak

FINAL REPORT

Contract No. NAS 9-8123

Volume 1

OCTOBER 1969

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NASA MANNED SPACECRAFT CENTER
RESEARCH AND DEVELOPMENT BRANCH
HOUSTON, TEXAS

 **SPERRY RAND** RESEARCH CENTER
SUDBURY, MASSACHUSETTS 01776

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PREFACE

This is the first of three volumes. Volume 2 consists of lists of mnemonic card names, card-pin interconnections and networks. Volume 3 is comprised of listings of interface signal characteristics, a map of the card layout in the rack and logic drawings.

TABLE OF CONTENTS

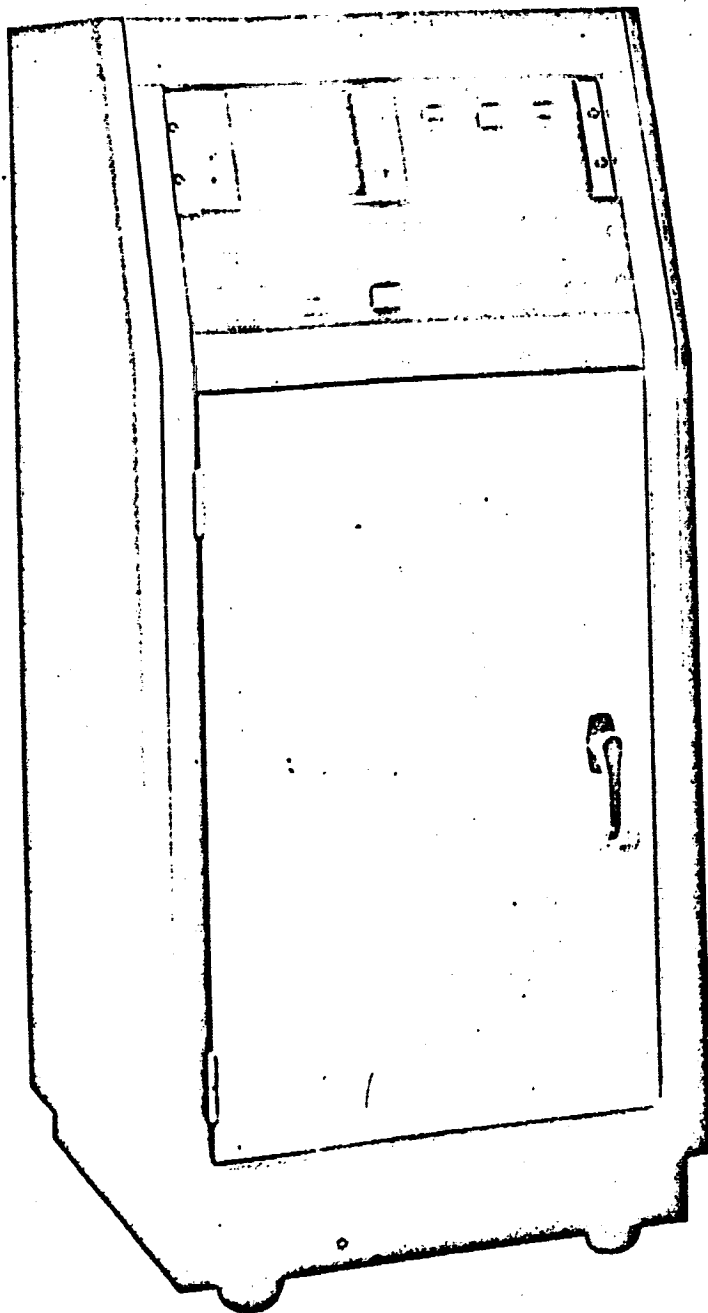
<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1
2	CALCULATIONS	6
3	DESCRIPTION OF HARDWARE IMPLEMENTATION	16
4	COMPUTER OPERATIONS	43
	APPENDIX A - A Method for Updating Direction Cosines in a Strap-Down Inertial Guidance System	A-1

LIST OF ILLUSTRATIONS

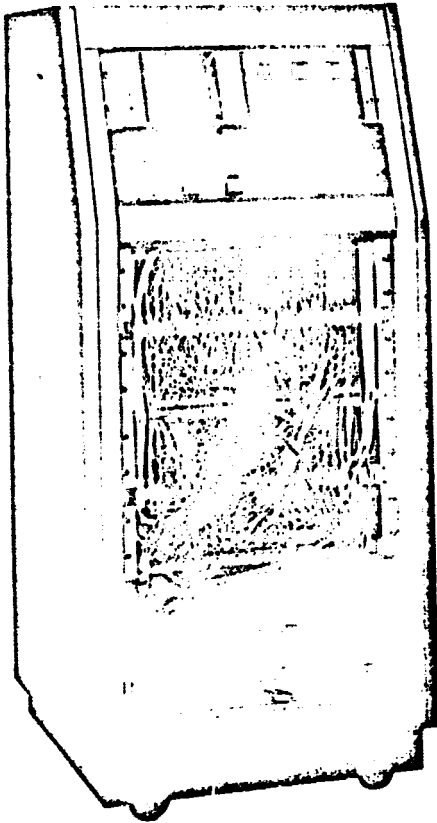
<u>Figure</u>		<u>Page</u>
1	Overall SIMU computer block diagram.	3
2	Direction cosine data register.	9
3	Computation block diagram.	9
4	Vector resolver detailed block diagram.	10
5	Euler angle computer block diagram.	12
6	Tape load, manual load and selected display block diagram.	18
7	Resolver timing chart.	21
8	Gyro input logic chain timing chart.	22
9	Gyro to direction cosine computer timing chart.	23
10	Accumulator update cycle self-contained portion timing chart.	24
11	Accumulator update cycle external portion timing chart.	25
12	Full update cycle timing chart.	28
13	Adder operation, accumulator card's internal computation timing chart.	29
14	Accelerometer ΔV input path timing chart.	30
15	Earth rate input logic chain timing chart.	30
16	Detail block diagram - Euler angle computer.	33
17	Euler comparison logic angle ψ timing point.	34
18	Sin/cosine generator detail block diagram.	35
19	Sign and quadrant determination logic.	36
20	Euler angle decimal display logic timing chart.	39
21	Eight-ball holding registers timing chart.	39
22	CRT display block diagram	40

LIST OF ILLUSTRATIONS (cont.)

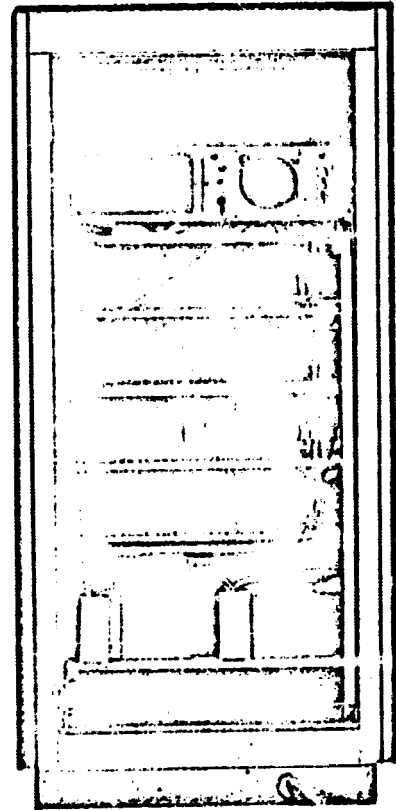
<u>Figure</u>		<u>Page</u>
23	Tape output block diagram.	42
24	Tape output format.	49



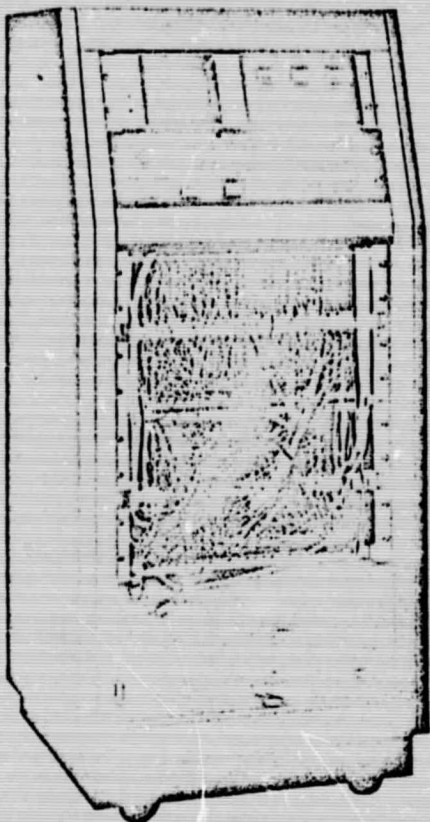
Front view of SIMU computer showing CRT character display and panel controls.



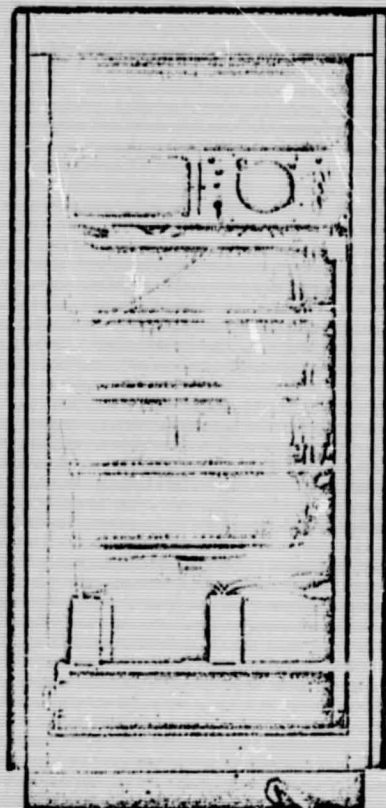
Front view with door removed showing backboard wiring and interface cables.



Rear view showing CRT chassis, logic cards and power supplies.



Front view with door removed showing backboard wiring and interface cables.



Rear view showing CRT chassis, logic cards and power supplies.

STRAPDOWN INERTIAL MEASUREMENT UNIT COMPUTER

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SECTION I

INTRODUCTION

The objective of this project was the design and construction of a specialized breadboard computer to perform the angular transformations associated with a strapdown inertial measurement unit (SIMU). In this report we shall first describe the overall functions performed by the system and then discuss the various sections which it comprises. In the last section of this report, connection and operating instructions for the computer are given.

Before the discussion of the system is commenced, a word or two in clarification of the objectives of the program is in order. The general problem associated with strapdown navigation systems is that of maintaining an accurate measure of the relative orientation of the rotating vehicle with respect to some reference system. The reference system may either be inertial space or some other system such as earth whose orientation and rotational velocity with respect to inertial space are known. Once the orientation of the vehicle is known, accelerations measured in the vehicle frame may be transformed and integrated to provide a position vector in the reference frame.

Several types of parameters, each with its relative merits, have been used to provide rotational coordinates for strapdown navigation. The system described here uses direction cosines. The reason for the selection of direction cosines was twofold. First, if a separate computer is to be employed to provide the angular transformations, the greatest simplicity appears to result from the use of direction cosines. Second, their use incurs no polar singularities.

Computation of direction cosines may be done by either general or special purpose computers. Special purpose computers that have been applied most often were digital differential analyzers (DDA's). The problem engendered by conventional DDA direction cosine computation is that of truncation error.

This error arises because a finite difference equation is used whose solution is not identical to that of the rotational differential equation that governs body motion.

A method of implementing the direction cosine calculations was developed at SRRC which makes use of a trigonometric transformation rather than an approximation to a differential equation. This method, explained in Appendix A, incurs no truncation error since it is an exact process. The method given in Appendix A, with slight modifications, is the basis for direction cosine computations used in the SIMU computer.

In addition to computing direction cosines, the SIMU computer performs several other functions which will be described shortly. The purpose in constructing this machine was to provide a laboratory system which would test both the methods of computation and the inertial sensors to which it will be connected. The design philosophy followed throughout was not to provide a system which could be repackaged, using the same basic components, to be flyable, but rather to provide a modifiable, modular computer which would be easily serviceable and from which later designs could be extracted for advanced electronic implementation. For this reason, off-the-shelf components (Texas Instruments Series 74N) were used for the logic and storage elements throughout.

A block diagram of the overall SIMU computer is shown in Fig. 1. The description of total system function is given with respect to this diagram. All inputs and outputs connect to SPICE, the interface unit. The SIMU computer receives three pulsed gyro and three pulsed accelerometer inputs. These inputs may be asynchronous, since synchronization is provided by the gyro and accelerometer sync units. The pulses are then scaled to the proper value for computation. These synchronized and scaled gyro pulses are introduced to the buffer. The buffer performs a pulse adding function; the algebraic sum of gyro and earth rate pulses occurring about a single gyro axis is taken at this point. If the magnitude of this sum exceeds unity, the excess is stored and introduced at the first available time. Allowable input rates are such that the excess never is more than one pulse.

The buffer output drives the direction cosine computer. This unit computes the set of nine direction cosines to a precision of 48 bits when input

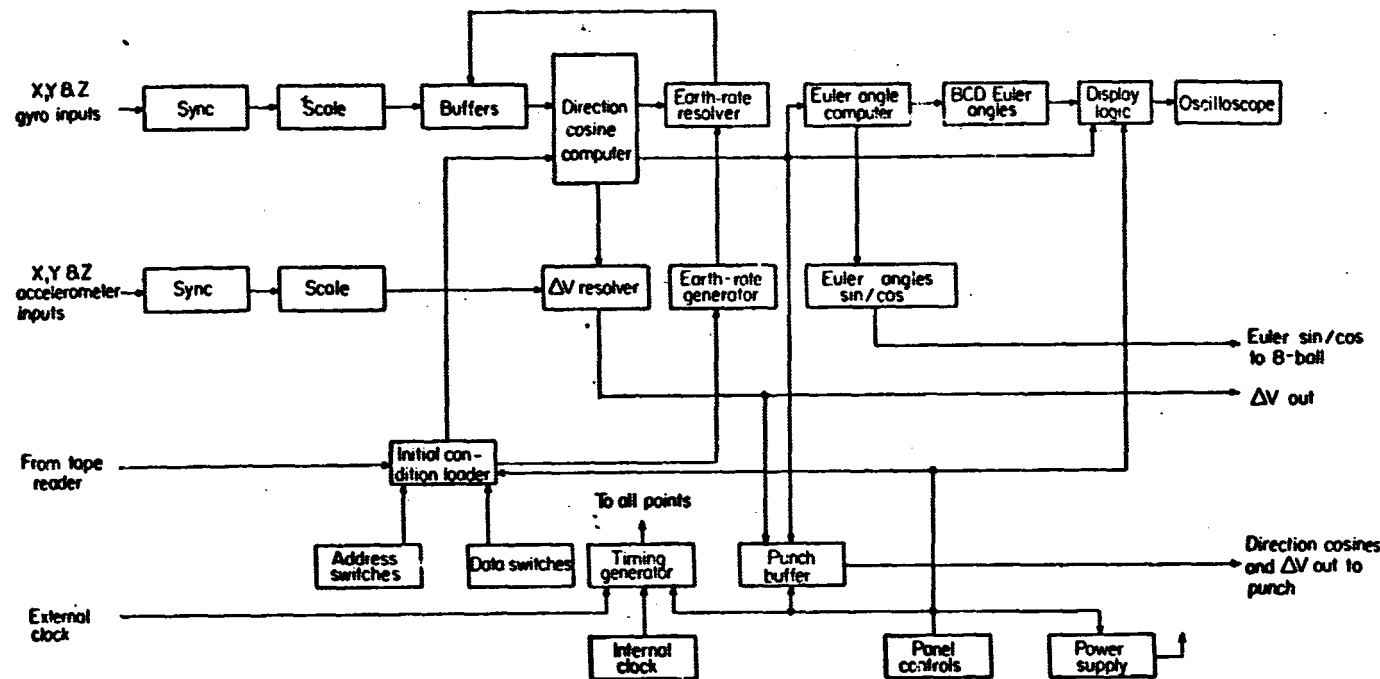


FIG. 1 Overall SIMU computer block diagram.

scale is set to 2^{-15} radians per pulse (approximately). Accelerometer signals in the form of increments of velocity enter the accelerometer scaling unit after synchronization. This unit allows the effective scale factors of all accelerometers to be made equal, a necessity if an angular transformation is to take place. The incremental velocity vector is transformed to the reference system by means of the earth rate generator. Increments in reference frame velocity are delivered directly as system outputs and accumulated to form whole words for subsequent time sampling and punch out.

The earth rate generator forms three pulse trains whose rates are proportional to the components, measured in the reference frame, of earth's rotation about the reference axes. If north-vertical orientation is used, then one of these components will be zero. The direction cosines are used to transform the earth rate signals to the vehicle frame by means of the earth rate resolver. These transformed rates are then added to the scaled gyro signals in the gyro buffers.

The interpretation of attitude from direction cosines is a confusing process. For this reason, an Euler angle computer is provided for display and eight-ball control purposes. This computer operates in a servo mode, starting from a set of reference angles and slewing the Euler angle generator until a set of internally-generated direction cosines matches the true set taken from the direction cosine computer. In this way, no cumulative errors are introduced when polar "gimbal-lock" regions are approached. A new set of Euler angles is displayed every 0.22 second. The angles are displayed to the nearest 0.01 degree. The sines and cosines of the Euler angles are provided as output to drive an external eight-ball display.

The primary operator display for the SIMU computer is a CRT character unit. Euler angles are displayed in a signed decimal format and direction cosines are displayed in octal notation. Three direction cosines to full precision or nine direction cosines to 16-bit precision may be displayed at any time. The Euler angles and direction cosines are selected and formatted in the display logic unit. This unit also generates the video and X-Y positioning information for the CRT.

Initial conditions for the various registers may be entered in three ways. The normal method makes use of a punched paper tape reader, connected through SPICE. Each register is assigned an address. Properly formatted tape containing address information and data will cause the initial conditions to be entered when computer is in the "Reader" mode. This loading is controlled by the initial condition loader. It is also possible to load any register manually (when the computer is in the "Manual" mode) by means of the switch register on the front panel. This is accomplished by setting the address of the intended register on the "Address" switches and the desired data word on the "Data" switches, and loading. The third method of initialization places the identity matrix in the direction cosine registers, but leaves all other registers unchanged. This is accomplished by placing the computer in the "Diagonal" mode and loading.

The computer contains the necessary storage, formatting, and control equipment to generate outputs for a paper tape punch. Direction cosines, accumulated velocity increments, and a time reference constitute the information which may be punched. These quantities are translated to octal form and an eight-bit ASCII code is generated to drive the punch input lines via SPICE. A "data ready" signal is also provided. Punch rates of 15, 30, and 60 characters per second are available through front panel control. Spacing and inter-block indexing characters are also generated.

All computer timing is derived from a single frequency source. A precision 20 MHz crystal clock is normally used but an input and suitable switching are provided for external clocking. The clock frequency is divided by four to give the basic 5 MHz bit rate used throughout most of the computer. All timing signals are supplied by the timing generator.

The 5 volt dc used for all computer units is produced by the power supply.

SECTION 2

CALCULATIONS

In this section, the methods used in performing various calculations within the computer are described. These calculations include (1) direction cosines, (2) velocity resolution, (3) earth rate compensation, and (4) Euler angles.

Direction Cosine Updating. The calculation resulting in direction cosine updating is performed essentially as described in Appendix A, with slight modifications which permit a 50% speedup in processing rate. Direction cosine updating is performed sequentially for each input axis in turn. The old direction cosine matrix is multiplied by 3 x 3 updating matrices to provide the new cosine matrix. The updating matrix sets for the x, y, and z input axes are, respectively

$$u_x = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1-h^2 & 0 \\ 0 & 0 & 1-h^2 \end{vmatrix} \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1-h^2 & 2h \\ 0 & -2h & 1-h^2 \end{vmatrix}$$

$$u_y = \begin{vmatrix} 1-h^2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1-h^2 \end{vmatrix} \begin{vmatrix} 1-h^2 & 0 & -2h \\ 0 & 1 & 0 \\ 2h & 0 & 1-h^2 \end{vmatrix}$$

$$u_z = \begin{vmatrix} 1-h^2 & 0 & 0 \\ 0 & 1-h^2 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1-h^2 & 2h & 0 \\ -2h & 1-h^2 & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

For each matrix set, the right and left matrices represent operations performed during the first and second updating cycles, respectively. As in the original updating method, the value of h is given by

$$h = \tan \frac{\theta}{2}$$

where θ is the increment of angle measured by the gyro and is adjusted to make the magnitude of h equal to some negative, integer power of two.

The formation of terms in the updating processes is best illustrated by means of a diagram. In Fig. 2, Y, R, and E represent n-bit shift registers which store the upper-, middle-, and lower- n bits of a number C. D is a one-bit delay and $h=2^{-n}$. The direction of shift is from left to right, so that as C exits from the output of E, $2hC$ exits from D and h^2C exits from Y. These quantities may be gated and transmitted to adders (as in Appendix A) to provide the updating matrix operations. Processing of the input axes is accomplished in the sequence (X,Y,Z) so that a complete input servicing requires six update cycles.

Earth Rate Compensation. The direction cosine matrix represents a transformation from vehicle to reference axes. Since these reference axes (e.g., Earth axes) may themselves be rotating with respect to inertial space whereas the gyro inputs represent rotations of the vehicle with respect to inertial space, it is necessary that corrections be applied at some point to allow proper reference axes. These corrections will be described next.

The computer direction cosine matrix, C_{re} , represents a transformation from rotating vehicle axes to earth-referenced axes. Then the transformation which takes a vector measured in vehicle axes, $\underline{V}_r$, to the same vector, measured in earth axes, $\underline{V}_e$, is

$$\underline{V}_e = \underline{V}_r C_{re} \quad (1)$$

The inverse transformation is given by

$$\underline{V}_r = \underline{V}_e C_{re}^{-1} \quad (2)$$

and since C_{re} is an orthogonal transformation,

$$C_{re}^{-1} = C_{re}^T \quad (3)$$

and

$$\underline{V}_r = \underline{V}_e C_{re}^T \quad (4)$$

The gyro input rates $\underline{w}_{ir,r}$ represent the angular velocity of inertial space with respect to the vehicle frame, as measured in vehicle coordinates. The angular velocity of the reference (Earth) frame with respect to the vehicle, as measured in vehicle coordinates, is

$$\underline{w}_{er,r} = \underline{w}_{ir,r} - \underline{w}_{ie,r} \quad (5)$$

where $\underline{w}_{ei,r} = -\underline{w}_{ie,r}$ is the angular velocity of the reference frame with respect to the inertial frame, as measured in vehicle coordinates. Finally, from Eq. (5)

$$\underline{w}_{er,r} = \underline{w}_{ir,r} - \underline{w}_{ie,e} C_{re}^T \quad (6)$$

where $-\underline{w}_{ie,e}$ is the angular velocity of the reference frame with respect to inertial space, as measured in reference coordinates. This defines the correction of gyro inputs for a noninertial reference system, and forms the basis of the earth rate correction computation. The correction computation is best illustrated by means of a simple block diagram (Fig. 3). This block includes the transformation of accelerometer signals, as will be described.

An earth rate generator produces the three components of earth rate with respect to inertial axes, as measured in the earth frame. These quantities are transformed to measurements in the vehicle frame by a vector resolver. The other input to the vector resolver is the transposed direction cosine matrix. The resolved earth rate signals are added to the gyro inputs in the buffer, and are used to drive the direction cosine computation. Accelerometer inputs, measured in the rotating frame, are transformed by another vector resolver to the reference frame. The direction cosine matrix itself is used as the other input to this resolver, in accordance with Eq. (6) above. A more detailed block diagram of a vector resolver is shown in Fig. 4. Since the form of the earth rate

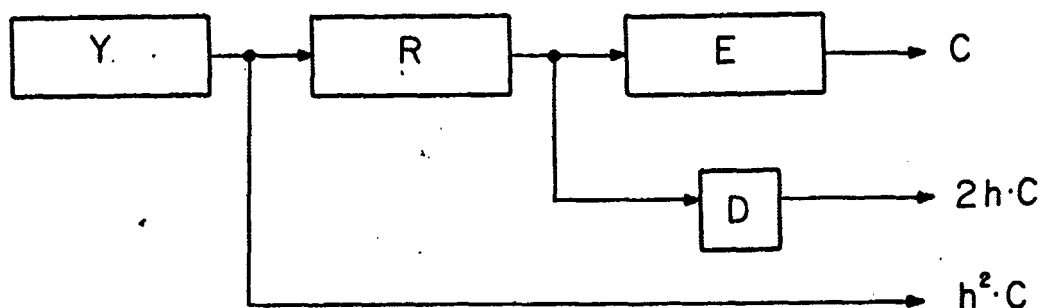


FIG. 2 Direction cosine data register.

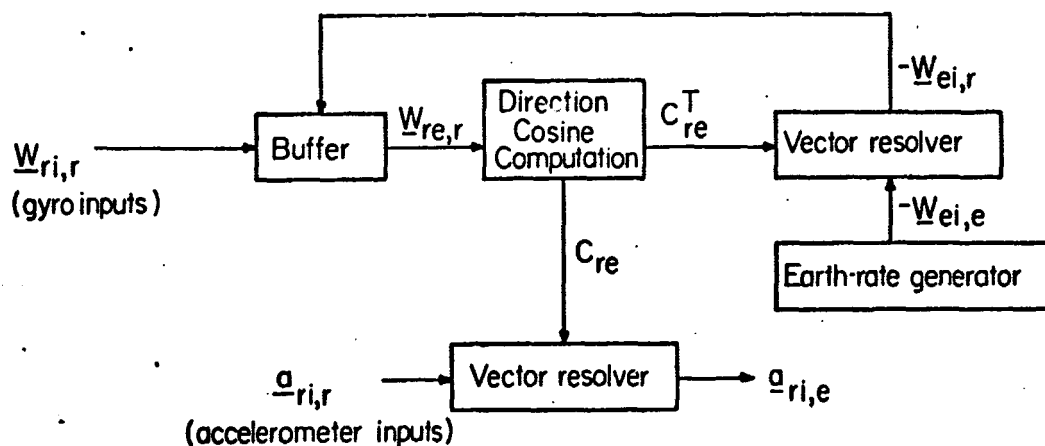


FIG. 3 Computation block diagram.

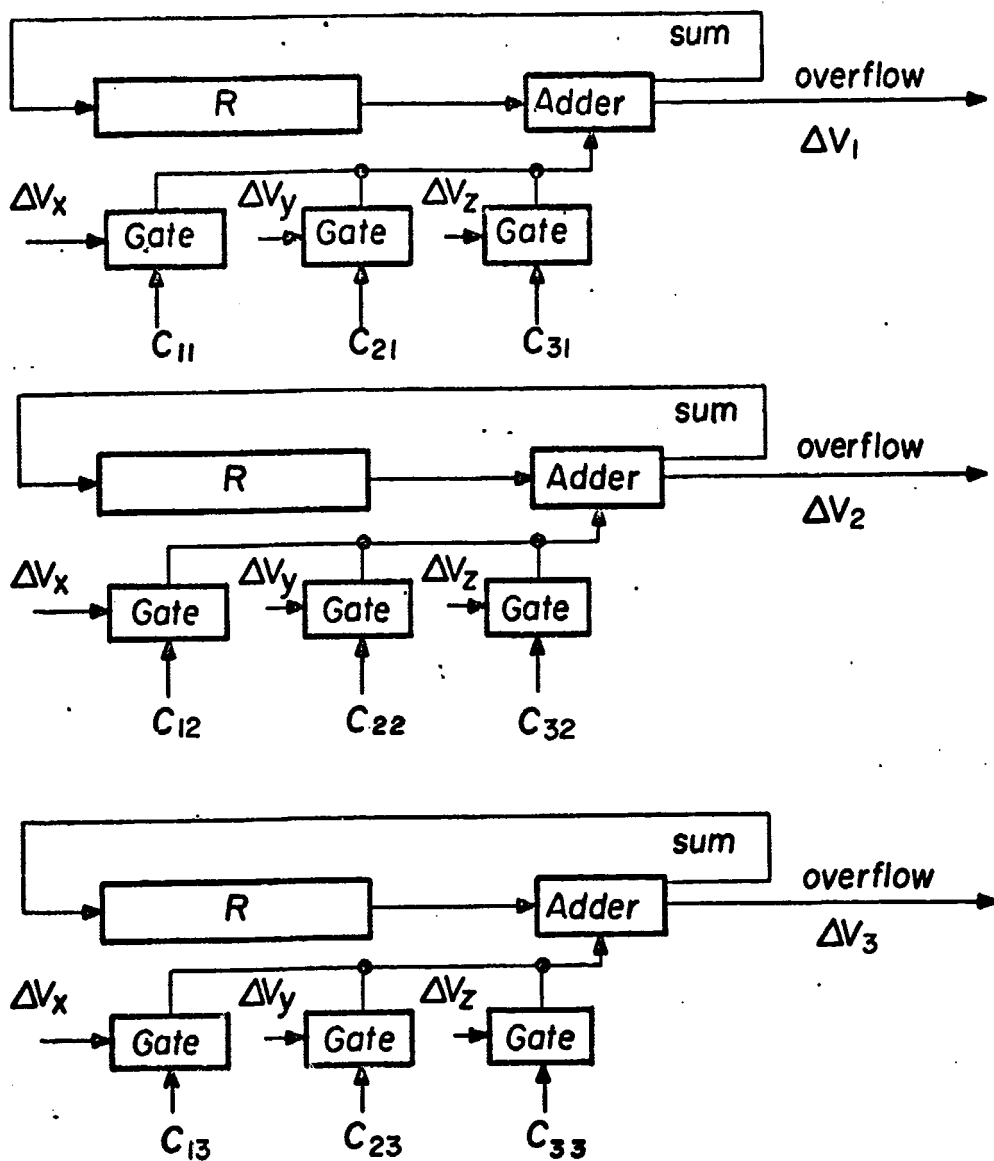


FIG. 4 Vector resolver detailed block diagram.

and accelerometer vector resolvers is the same, with the only difference being in the use of the transposed cosine matrix in one case. a description of the resolution of accelerometer inputs will serve to illustrate both functions.

Velocity Resolution. Each scalar resolver contains a shift register (R), a serial adder, and three input gates. The input gates cause a serial input variable (C_{ij}) to be multiplied by a ternary variable (V_k). The ternary variable has allowable values (-1, 0, +1) corresponding to negative, zero, and positive values of the input increment, respectively. The gates are also time-sampled so that no two of them may deliver inputs to the adder during any cycle. The adder has two outputs. One of these is the sum of the two inputs; the other is a ternary variable indicating sense and magnitude of overflow. When no overflow occurs, the sum of the gated input and the previous contents of the shift register are returned to the shift register. In the event of an overflow, the residue is returned to the shift register. It may be shown that the output overflow rate of any of the three scalar resolvers which comprise the vector resolver is given by :

$$r_k = C_{1,k}r_x + C_{2,k}r_y + C_{3,k}r_z$$

where r_x , r_y , and r_z are the input rates.

Euler Angle Computer. One of the outputs which can be obtained from the SINU computer is a set of Euler angles which relates the orientation of the platform axes to a set of reference axes. The required angles are: pitch (θ), azimuth (ψ), and roll (ϕ). The direction cosine logic (Fig. 5) computes a set of trigonometric functions of the Euler angles, from which the angles can be computed. The method used to calculate the Euler angles eliminates cumulative errors and thereby minimizes the problem of loss of accuracy near the poles by periodically (about 4.5 times per second) resetting the output registers and then slewing to the correct values as determined from updated values of the direction cosine matrix elements. The slewing operation is accomplished by counting (in a display counter or output register) the angular increment pulses applied to a sine-cosine generator which computes $\sin \alpha_c$ and $\cos \alpha_c$, as the generator is incremented from 0° to the required angle.

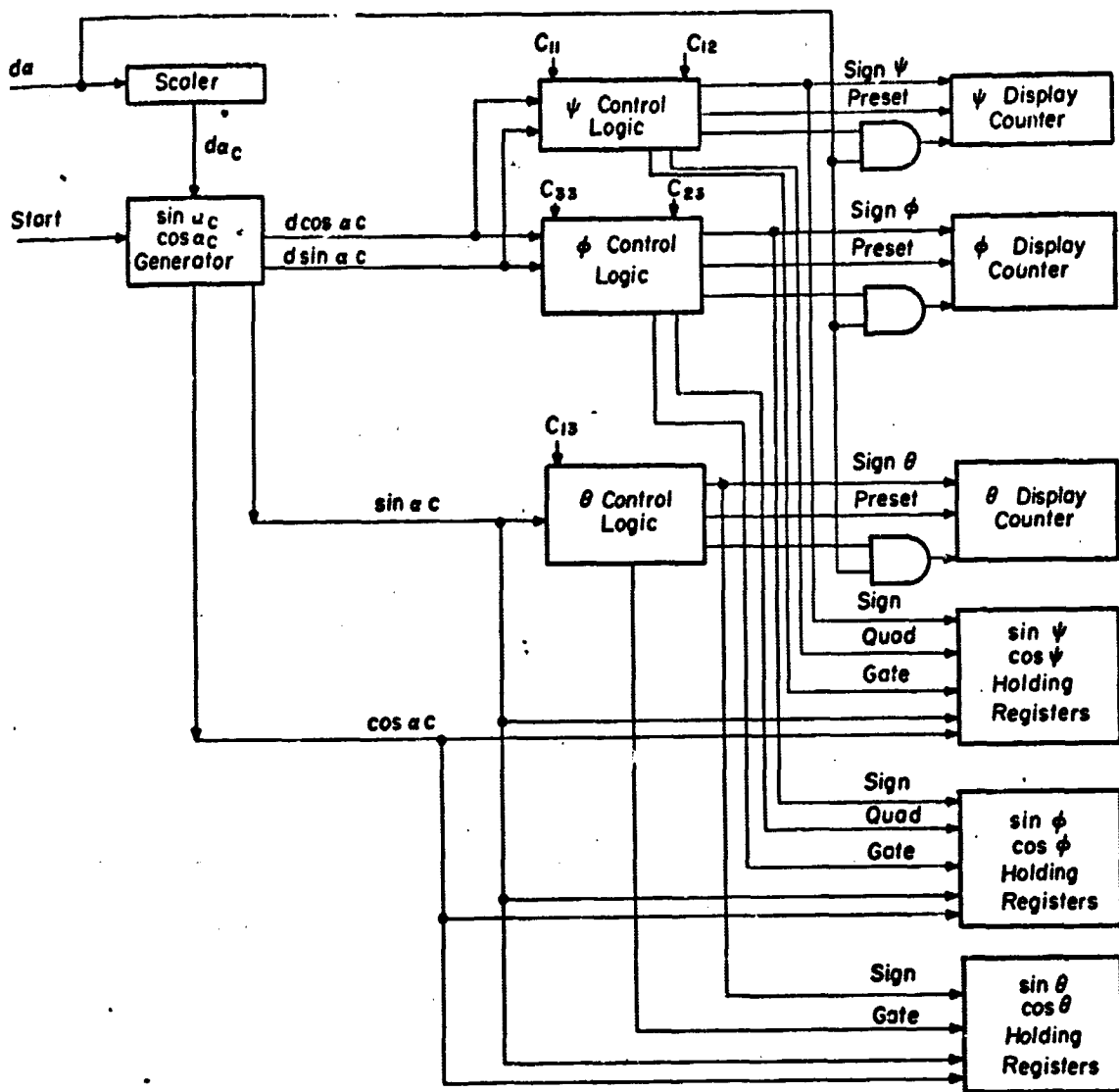


FIG. 5 Euler angle computer block diagram.

The increment pulses are gated into the counter by a signal from an error sensing circuit which is initialized with the appropriate elements of the updated direction-cosine matrix and driven by signals from the sine-cosine generator. The scaler at the input to the sine-cosine generator is provided so that the count of pulses in the BCD counter will have the proper scale to be displayed in degrees. The direction cosine elements used in the conversion are

$$\begin{aligned} c_{11} &= \cos \theta \cos \psi & ; & & c_{12} &= \cos \theta \sin \psi & ; & & c_{13} &= -\sin \theta & ; \\ c_{23} &= \cos \theta \sin \phi & ; & & c_{33} &= \cos \theta \cos \phi \end{aligned}$$

The pitch control logic is simplest since $c_{13} = -\sin \theta$ and θ can lie only in the 1st and 4th quadrants. $\sin \alpha_c$ is compared with $|C_{13}|$, and $d\alpha$ pulses are gated into the display counter until $\sin \alpha_c > |C_{13}|$. The sign of θ is the complement of the sign of C_{13} .

The computation of the remaining Euler angles is best illustrated by an example. Assume that roll angle ψ lies in the first quadrant and that ψ_c is the computed value of ψ . The error E_ψ may be defined as

$$E_\psi = \cos \theta \sin(\psi_c - \psi)$$

When $\psi_c = \psi$, $E_\psi = 0$. Expanding this error equation,

$$E_\psi = \cos \theta \cos \psi \sin \psi_c - \cos \theta \sin \psi \cos \psi_c$$

When equivalent values for the direction cosines are substituted into the error equation, it becomes

$$E_\psi = C_{11} \sin \psi_c - C_{12} \cos \psi_c$$

This solution is implemented by reducing E_ψ in increments until it is equal to zero. The incremental equation is

$$dE_{\psi} = C_{11} \cos \psi_c d\psi_c + C_{12} \sin \psi_c d\psi_c$$

In order to economize on equipment, a single sine-cosine generator may be used jointly by the three angle computers. This generator produces incremental outputs $\sin \alpha_c d\alpha_c$ and $\cos \alpha_c d\alpha_c$. The common error equations used for azimuth and roll then become

$$E_{\alpha} = \cos \theta \cos \alpha \sin \alpha_c - \cos \theta \sin \alpha \cos \alpha_c$$

$$dE_{\alpha} = \cos \theta \cos \alpha \cos \alpha_c d\alpha_c + \cos \theta \sin \alpha \sin \alpha_c d\alpha_c$$

where $\cos \theta \cos \alpha$ and $\cos \theta \sin \alpha$ are obtained from the direction cosines according to Table 1. The angle α is the difference between the magnitude of the angle to be calculated and the value preset into the counter (i.e., 0° or 90°), and is therefore always less than 90° .

TABLE 1

Quadrant	$\cos \theta \cos \alpha$		$\cos \theta \sin \alpha$		E_{α_0}		Preset
	ψ	ϕ	ψ	ϕ	ψ	ϕ	
1	C_{11}	C_{23}	C_{12}	C_{23}	$-C_{12}$	$-C_{12}$	0°
2	C_{12}	C_{23}	$-C_{11}$	$-C_{33}$	C_{11}	C_{33}	90°
3	$-C_{12}$	$-C_{23}$	$-C_{11}$	$-C_{33}$	C_{11}	C_{33}	90°
4	C_{11}	C_{33}	$-C_{12}$	$-C_{23}$	C_{12}	C_{23}	0°

The initial value, E_{α_0} , obtained by setting $\alpha_c = 0$ in the equation above is $\cos \theta \sin \alpha$. Since $|\theta| < 90^\circ$ and $0^\circ \leq \alpha < 90^\circ$, E_{α_0} is always negative. The calculation is started by loading the appropriate direction cosines (from Table 1) and E_{α_0} . At the same time the sine-cosine generator is set to $\alpha_c = 0$, and the display counter is preset to 0° or 90° depending on the quadrant of ψ or ϕ . Calculation proceeds until E_{α} goes to zero; then the pulse drive to the display counter is inhibited and $\alpha_c = \alpha$.

The sines and cosines of the Euler angles are also made available to drive an eight-ball display. When the error conditions of the control logic are satisfied, the current values in the sine-cosine generator are transferred to the appropriate holding registers. During the transfer the sign of the sine and cosine are corrected for quadrant. When in the second or third quadrants, ψ and ϕ also require an interchange of sine and cosine values.

SECTION 3

DESCRIPTION OF HARDWARE IMPLEMENTATION

Timing. There are two main groups of timing signals available in the computer. Those that are used in the complete update of the direction cosine matrix and those that are used to time the Euler angle update cycle.

The basic signals for the direction cosine matrix are:

1. Clock T and clock $\bar{T}$ which are used as the basic computer timing pulses. They occur every 200 nsec and are used by the elements that require positive going and negative going edges respectively to trigger.
2. Bit times B1 through B16 designate 16 sequential timing periods of 200 nsec each that make up a word time.
3. Word times W1 through W3 consist of 16 bits each. One word time is the normal resolver period and a 3 word period allows processing of the entire 48 bits of accumulator data.
4. Update 1 and update 2 are the two phases of the update around a given axis for the direction cosine matrix. Each one is three words long.
5. P1, P2 and P3 are the periods required for the two phase update around the x-axis, y-axis and z-axis, respectively. Taken together they are a complete update cycle for the direction cosine matrix. This occurs in 288 bit times or 57.6 μ sec.

The Euler angle update generator consists of several counters whose basic timing rate is the full direction cosine update cycle of 57.6 μ sec. Maximum count used is E3872 which is 223 msec long. During this time the sin/cos generator cycles through 90° , after which EBW is set at 204 msec to allow transfer of data to the eight-ball inputs. Earth rate input to its scale factor resolvers occurs once for every Euler angle update cycle and is therefore approximately 4.4 pulses per second. Clock signals are generated on cards C07 to C13.

Controls. Switches are provided on the computer panel to control the mode of operation and to load and display data. The switches provide 0 volts or +5 volt levels to the computer. All pulse train switching or pulse forming is done by logic circuits in the computer.

The computer can be driven by the internal 20 MHz crystal oscillator or an external clock in order to synchronize computer operation with other equipment. Pin CC on the SIMU/SPICE connector is used for the external clock signal. The CLOCK-INTERNAL/EXTERNAL switch on the control panel selects the desired pulse source. The logic required to switch between clock sources is located on Timing Board A.

The MODE switch and the START-STOP switch controls the computational mode of the computer. When the RUN mode is selected and the START-STOP switch is in the START position, the computer will process gyro and accelerometer inputs and compute the earth rate compensation. The action of the START-STOP switch is synchronized with the computer clock. The gating and synchronizing circuitry is located on Timing Board F.

The SCALE switch selects the desired value of a gyro input at the direction cosine matrix. At full scale, the values of the angular increments are 2^{-15} radians. The scale can be increased by factors of two to 2^{-12} radians. This scale change is effected by gating the clock pulses which drive the accumulators. The clock gating logic is located on Timing Board F.

The block diagram of the logic required to load and display the contents of the registers is shown in Fig. 6. Each 16 bit register is specified by a two character decimal address. The accumulators are treated as three separate 16 bit registers. The register address assignments are given in Table 2. The desired register is selected by the eight ADDRESS switches on the control panel. The switch settings are transferred into the Address register and are decoded as two hexadecimal characters. Characters 0 to 9 are used to specify registers.

The 16 bit light register on the panel displays the contents of the data register. When the MODE switch is in the RUN, MANUAL, or DIAGONAL positions the contents of the register specified by the address switches are loaded into the data register every 10 msec and displayed in the lights. When the MODE switch is in the READER position, the lights display the characters received from the tape unit as they are assembled in the data register.

The MANUAL position of the MODE switch enables data to be loaded from the 16 DATA switches. The contents of the DATA switches are transferred to

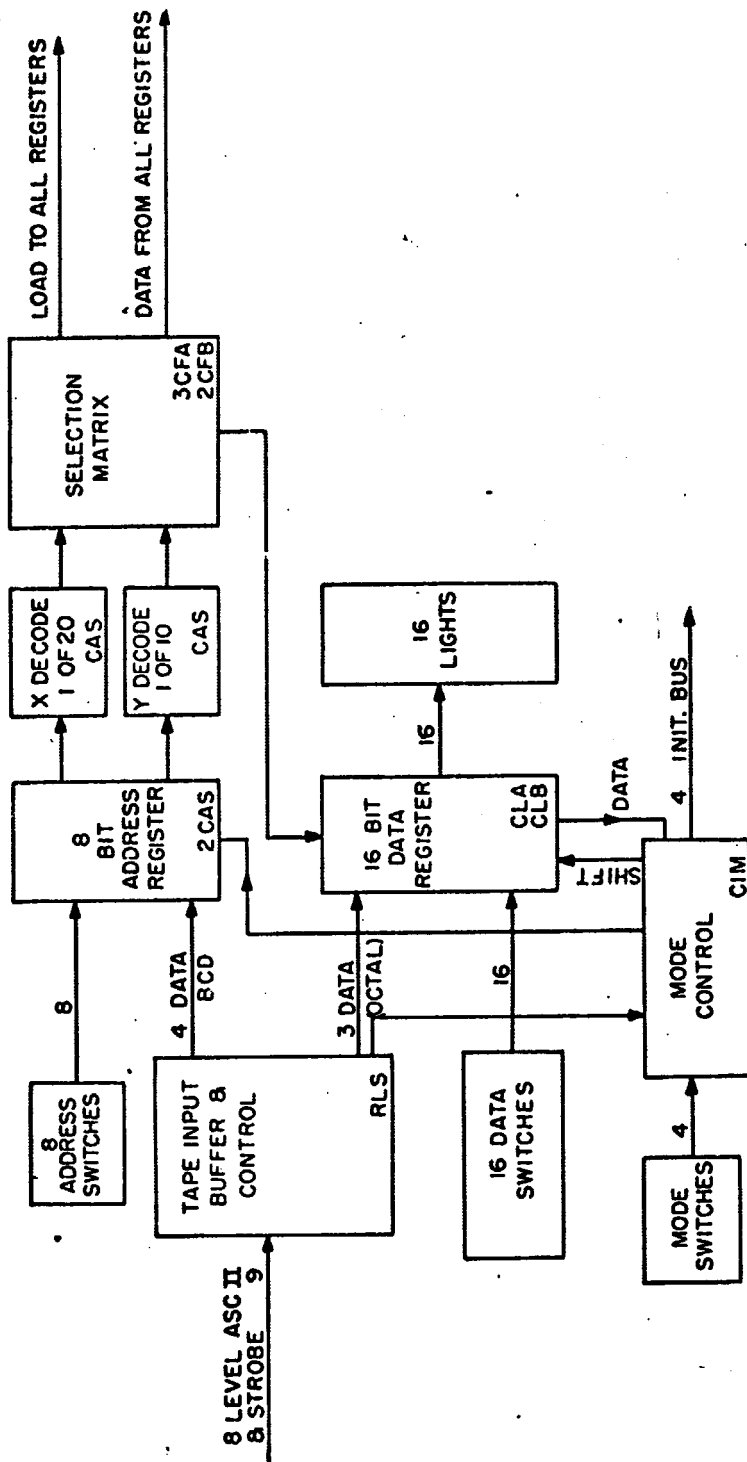


FIG. 6 Tape load, manual load and selected display block diagram.

the data register and a load cycle is initiated by pressing the LOAD switch. The load cycle allows the selected register to accept data while the contents of the data register are circulated on the INIT bus. The new contents of the register are displayed by the lights at the next display cycle.

The DIAGONAL position of the MODE switch allows the direction cosine matrix to be diagonalized and the resolvers to be set to 1/2 maximum value by pressing the LOAD switch. The address assignments are grouped so that all accumulators and resolvers can be selected simultaneously without selecting the shift registers which are used to store constants. The INIT bus is actually 4 separate buses, and each bus has the appropriate data during the diagonalize sequence. The IOND bus is connected to the accumulators on the main diagonal of the direction cosine matrix. The IOFD bus is connected to the off-diagonal accumulators. The IRES bus is connected to the resolvers. The ISRS bus is connected to the shift registers which hold constants and scale factors.

Tape Input. The READER position on the Mode switch allows the computer to load the registers from paper tape. An eight stage shift register on the Reader Loader Sequencer card controls the routing of the incoming characters to the Address register and the Data register.

The characters are coded in ASCII code. The numeric characters "0" to "9" and the alphabetic character "A" are used. All other characters are ignored by the computer. The characters are accepted on the trailing edge of the strobe pulse which occurs at the center of a character period. Input rates up to 20 kHz can be handled.

The character "A" initiates the load sequence by clearing the shift register and setting a flip-flop to "ONE". This "ONE" is then shifted through the shift register by the next eight numeric characters. The first two numeric characters following an "A" are loaded as decimal numbers into the Address register. The next six numeric characters are loaded into the data register as octal numbers. When the final character is loaded into the data register, a load sequence similar to the manual load sequence is initiated. The contents of the data register are transferred to the specified register. The computer is then ready for the next "A" character.

Resolver. A resolver is used to add either a single bit or full data word, serially to a stored data word. Subtraction of data from the stored value or any sequence of additions and subtractions may be performed. The resolver stores the magnitude and sign of any overflow for use during the next word time.

As shown in Fig. 7, incoming data is gated onto the resolver card and added bit by bit to the current contents of the shift register. Then the new data is reloaded into the shift register and circulated until the next update occurs. When a positive or negative one is sensed by $\overline{B16}$ strobing, the overflow magnitude and overflow sign flip-flops are set for the next word time. There are 30 resolvers in the computer.

Shift Register. The shift registers are used to store 16 bit words of information in the computer. There are 2 enable inputs available for each shift register's loading purposes. Output is continuously available and transfer may be started at any desired word time.

Gyro Sync and Buffer. The gyro pulses are sent to the SIMU interface as GXP, GXN, GYP, GYN, GZP and GZN. The signals are positive-going pulses representing positive or negative angular increments at a maximum repetition rate of 17.3 kHz (a minimum period of 57.6 μ sec). These pulses go first to the gyro sync portion of input card GAB. Figure 8 shows the input path.

The gyro sync circuit on the sync and buffer card synchronizes the incoming signals and a one word long (W2) pulse per period of $\Delta\theta_1$, $\Delta\theta_2$ or $\Delta\theta_3$ to its scale resolver (note Fig. 9) timed enough in advance of the moment when, for instance, the $\Delta\theta_1$ pulse is supposed to come to allow the direction cosine updates (see Figs. 10 and 11). The gyro scale resolver accumulates bits for each $\Delta\theta$ increment depending on its shift register's contents. Overflow of this resolver goes to the gyro buffer which algebraically sums the inputs from the earth rate resolvers and gyro scale resolvers. If the sum at any sampling time 0.5 ± 2 , one increment is stored for the next update period, and the other is gated through the switch box to enable the direction cosine update at the allotted time. The stored increment is held in the buffer until cancelled or until no new gyro input occurs. At that time the storage flip-flop is reset and the stored increment updates the direction cosine matrix.

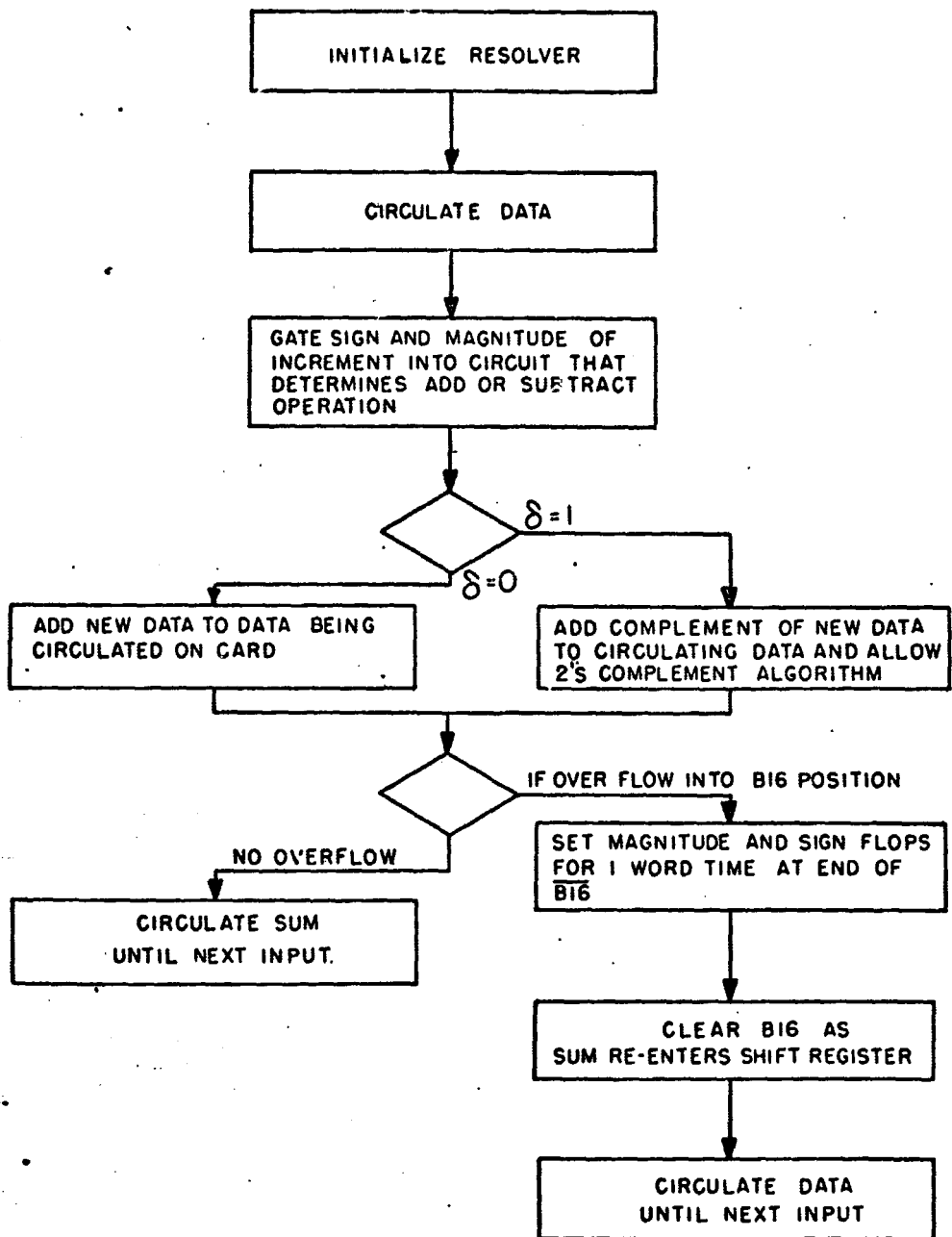


FIG. 7 Resolver timing chart.

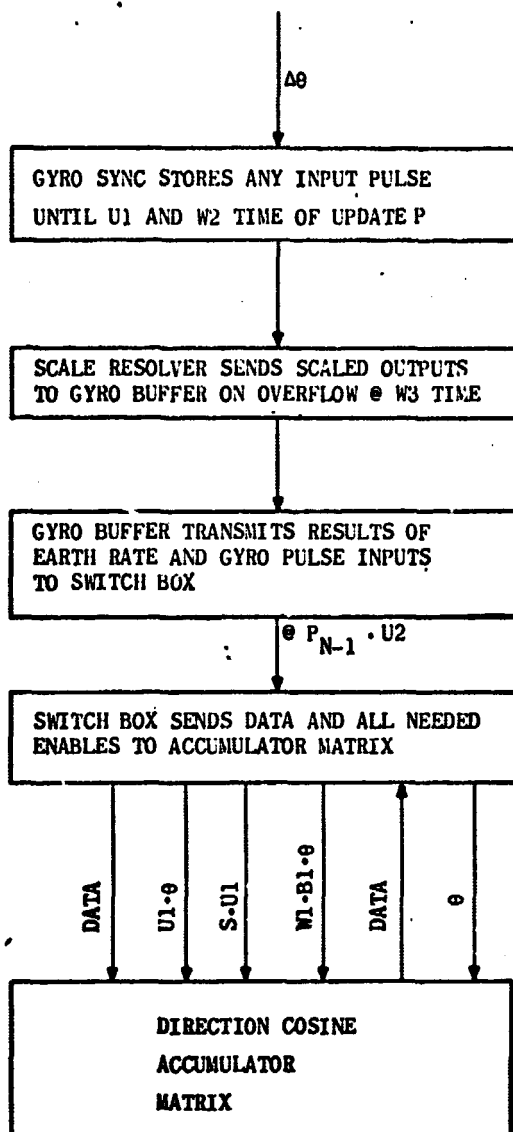


FIG. 8 Gyro input logic chain timing chart.

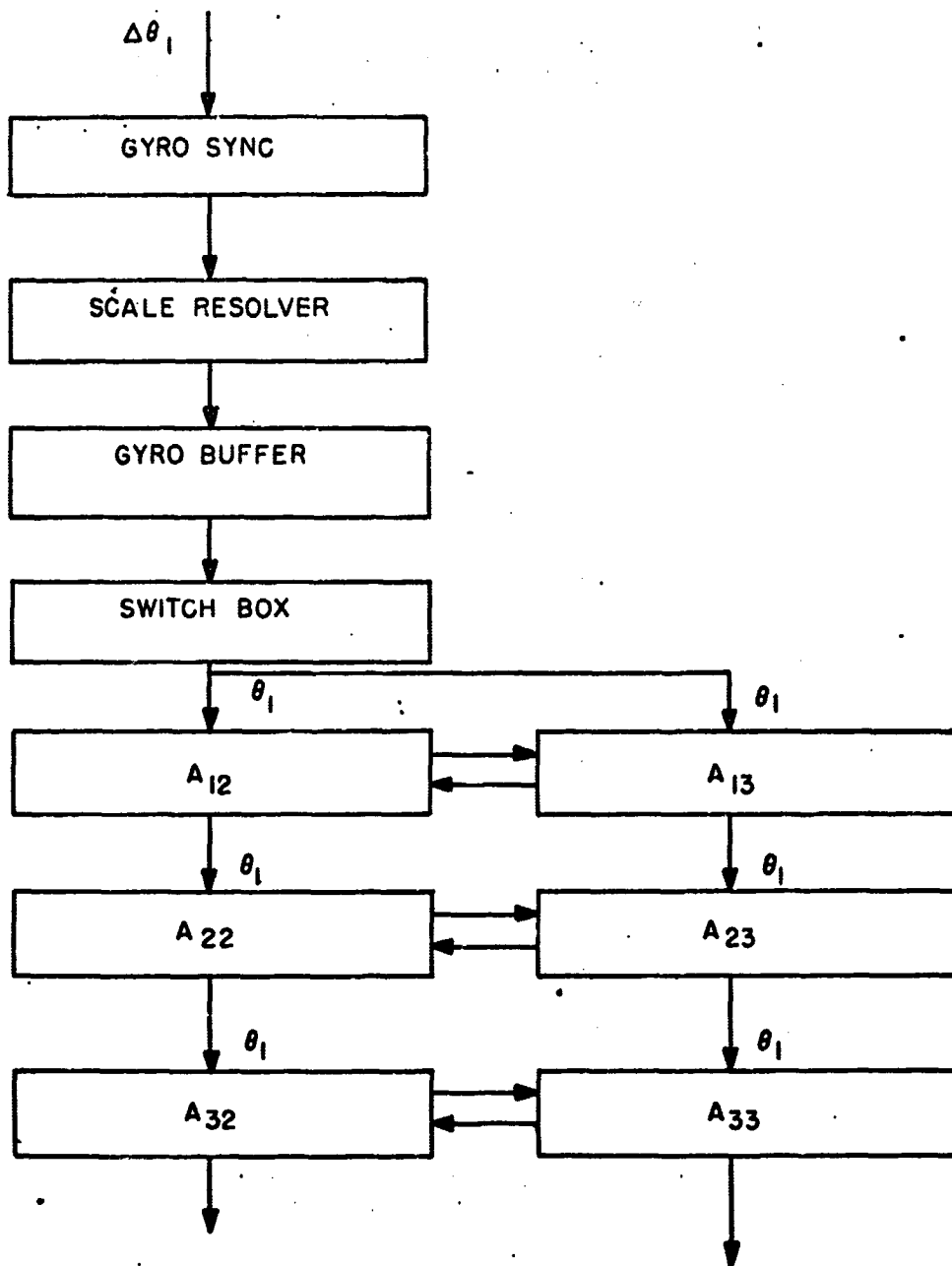


FIG. 9 Gyro to direction cosine computer timing chart.

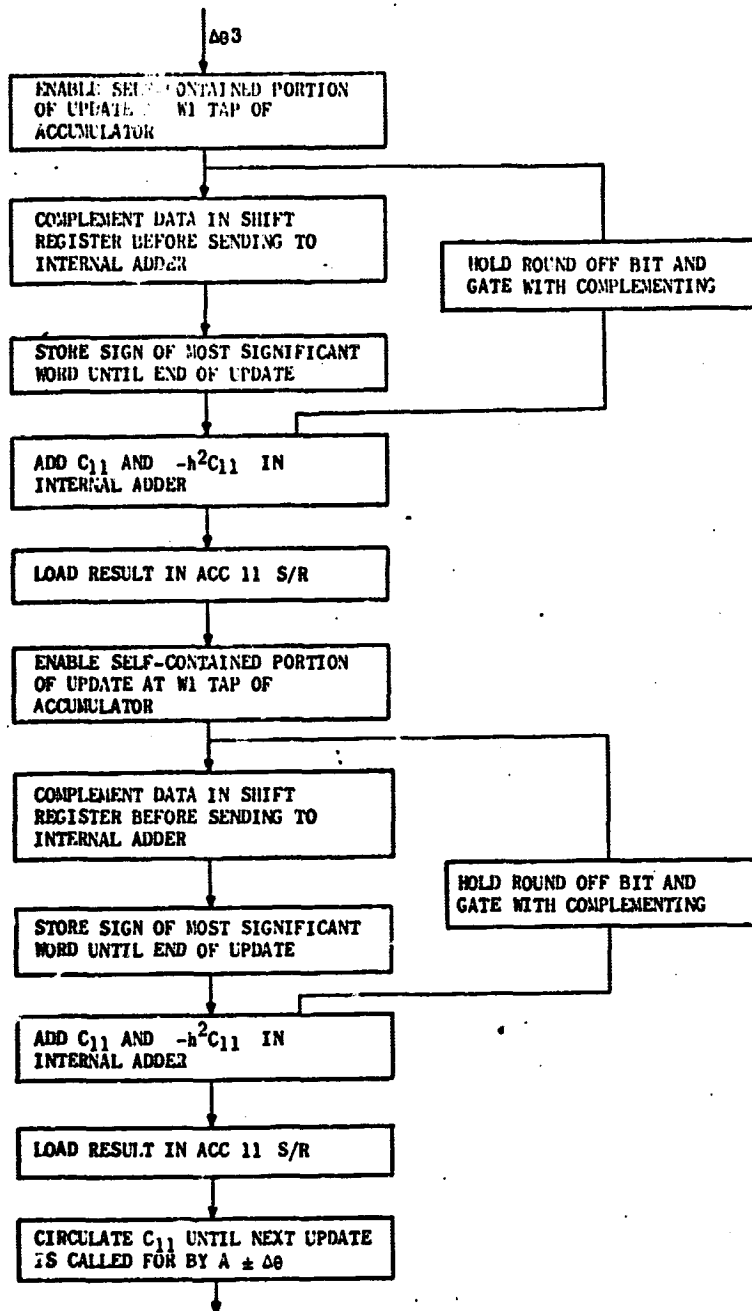
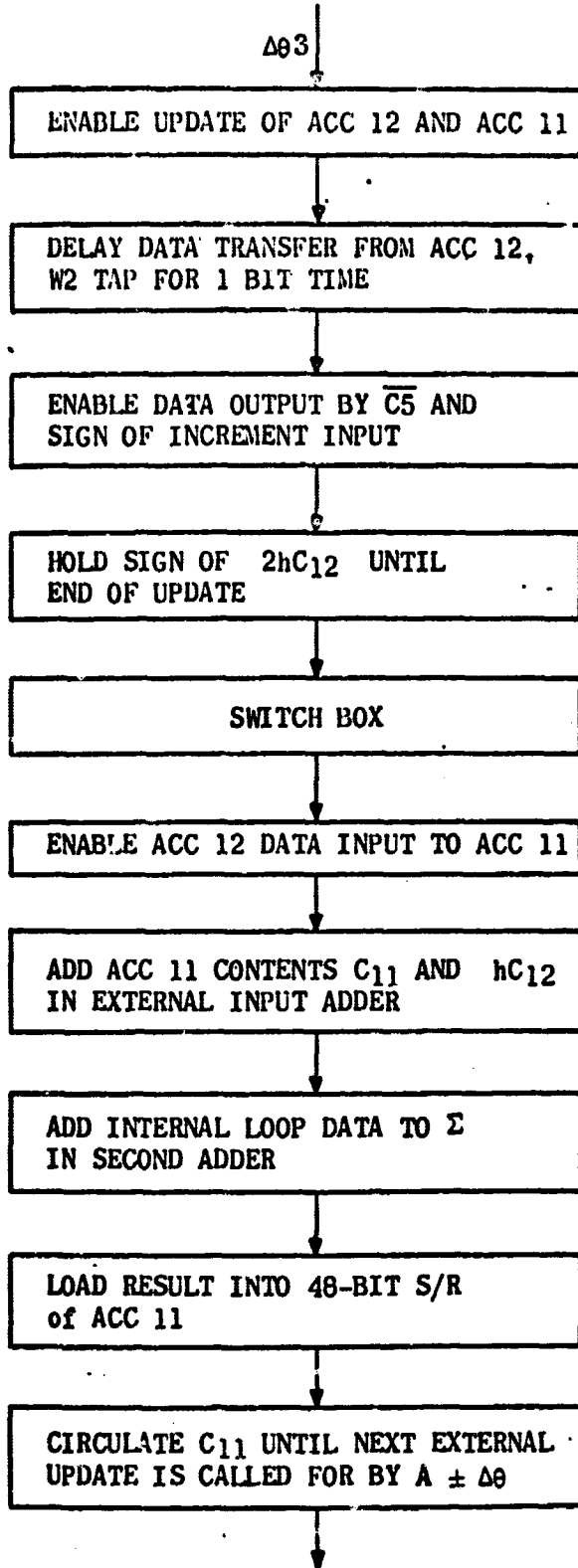


FIG. 10 Accumulator update cycle self-contained portion timing chart.



ACCUMULATOR UPDATE CYCLE
EXTERNAL PORTION
(ACCUM "1" $\rightleftharpoons$ ACCUM "2")

FIG. 11 Accumulator update cycle external portion timing chart.
 (Accum "1" $\rightleftharpoons$ Accum "2")

Direction Cosine Matrix. All three sets of accumulators that hold the values of the direction cosines are updated simultaneously (see Fig. 12) according to the equations:

$$\begin{aligned} C'_{11} &= C_{11}(1 - h^2) + 2hC_{12} \text{ initial} \\ \text{1st update } C'_{12} &= C_{12}(1 - h^2) - 2hC_{11} \text{ initial} \\ C'_{13} &= C_{13} \end{aligned}$$

$$\begin{aligned} C''_{11} &= C'_{11}(1 - h^2) \\ \text{2nd update } C''_{12} &= C'_{12}(1 - h^2) \\ C''_{13} &= C'_{13} \end{aligned}$$

It can be seen, taking C_{11} as an example, that there are basically three parts to the implementation of the equations. There is the addition of $\pm 2hC_{12}$ to the value of C_{11} for the external portion of the computation and the double operation of C_{11} having h^2C_{11} subtracted from it. The external operation and the first internal operation are done simultaneously during the first update of the period in the two adders on the accumulator card. The second internal computation is done during the second update of the period. For the derivation of the equations see the calculation section of this report.

Figure 13 shows the adder operation on the accumulator card for the internal computation. This is typical of adder operation on the Accumulator and Resolver cards.

Accelerometer Sync, Buffers and Resolvers. The accelerometer pulses are sent to the SIMU interface as AXP, AXN, AYP, AYN, AZP and AZN. The input signals have the same electrical characteristics as the gyro input pulses discussed previously. They represent positive and negative increments of velocity with the same repetition rate range as the gyro pulses. These pulses go to the accelerometer sync portion of input cards GAB or GAS. See Fig. 14 for the input path.

The accelerometer sync circuit on the sync and buffer card is used to provide an update (U2) pulse during the proper period for a ΔV_1 , ΔV_2 , or ΔV_3 pulse to allow the operation of its scaling resolver and the proper timing of the direction cosine matrix transformation.

The scale resolver accumulates bits for each ΔV increment depending on its shift register's contents. Overflow of the resolver goes to the triple input resolver that transforms the scaled body referenced increments to inertially referenced increments. These increments are accumulated in another resolver to provide a second output, a position vector that is the sum of the inertially referenced increments.

Earth Rate Compensation. The basic earth rate pulse train (Ω_E) is generated as part of the Euler timing countdown. Pulse rate is 4.47 Hz and pulse duration is a full update period P1-P2-P3. The pulse train Ω_E is gated by the RUN flip-flop to prevent extra inputs on start-up or in other modes of operation. The gated Ω_E pulse train drives resolvers $R\Omega_{E1}$, $R\Omega_{E2}$, and $R\Omega_{E3}$ whose overflow outputs are pulse trains with proportional rates, respectively, to the three components of earth rate about the reference axes (see Fig. 15). Inputs to these resolvers are timed to occur during W1-U1 of each resolver's particular update period (i.e., either P1, P2, or P3).

The outputs of resolvers $R\Omega_{E1}$, $R\Omega_{E2}$, and $R\Omega_{E3}$ drive the three triple input resolvers $R\Omega_1$, $R\Omega_2$, and $R\Omega_3$ wherein the transformation from earth to vehicle reference is obtained. The scaling of the outputs of resolvers $R\Omega_1$, $R\Omega_2$, and $R\Omega_3$ is made equal to that of the gyro inputs so that these pulse trains may be added to the scaled gyro pulses by the gyro buffers. The gyro buffers are designed to accept sign and magnitude pulse trains from the gyro and earth rate sources and deliver sign and magnitude pulse trains proportional to the sum of the two input rates. It is possible, during a single update period, for an earth rate-to-vehicle-frame transformation resolver to deliver two or three output pulses. However, two of these will be of different sign. An adapter is used to count these outputs algebraically and reduce the number of earth rate pulses sent to the buffer to, at most, one. Details of the adapter are shown in the logic diagram of GAC. Following processing by the adapters, scaled increments of earth rate go to the gyro buffer circuits where they are processed

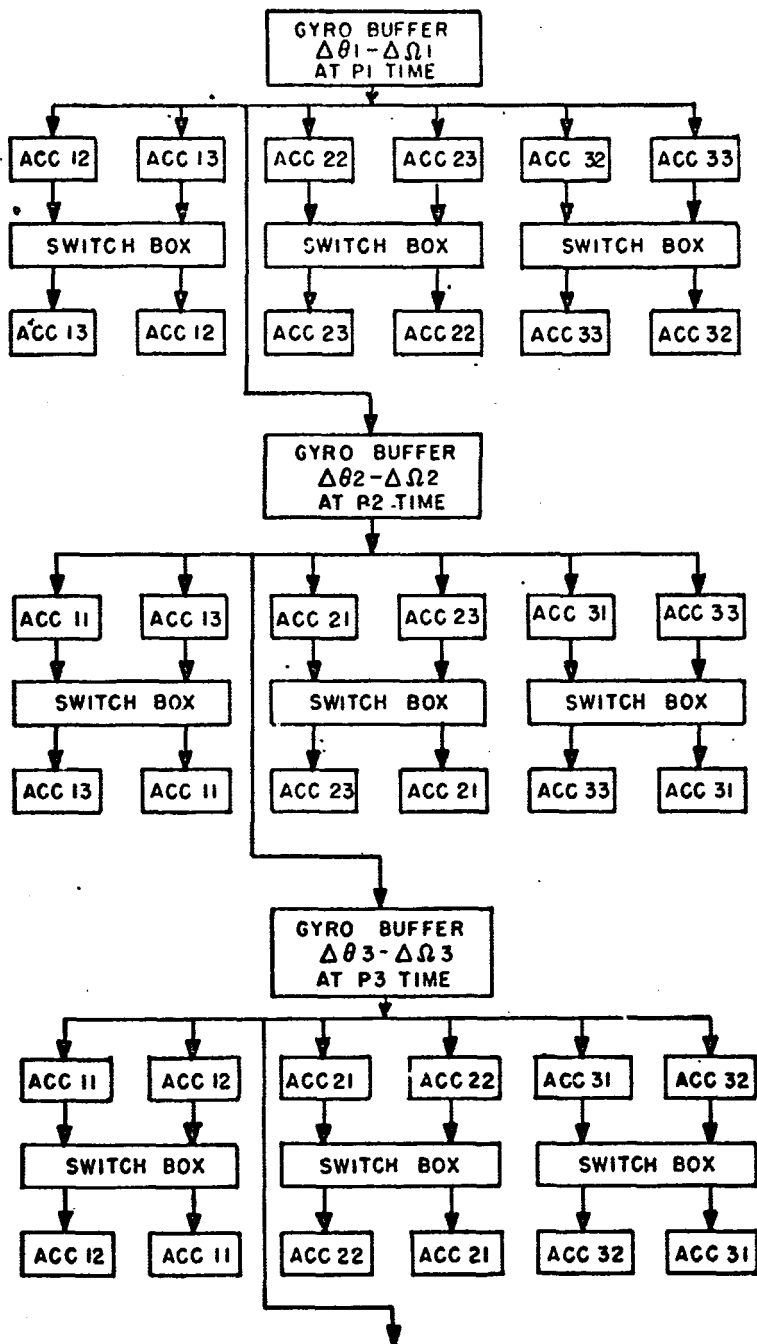


FIG. 12 Full update cycle timing chart.

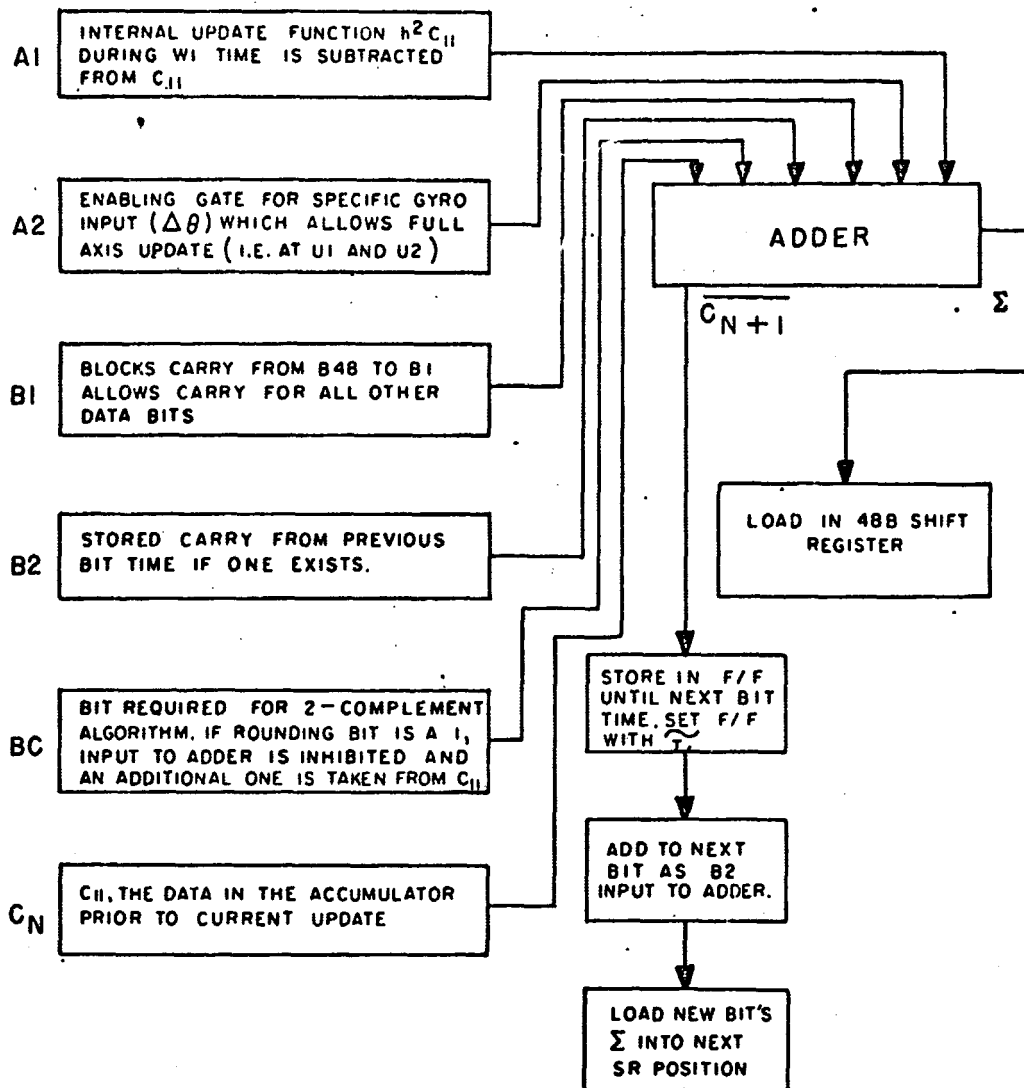


FIG. 13 Adder operation, accumulator card's internal computation timing chart.

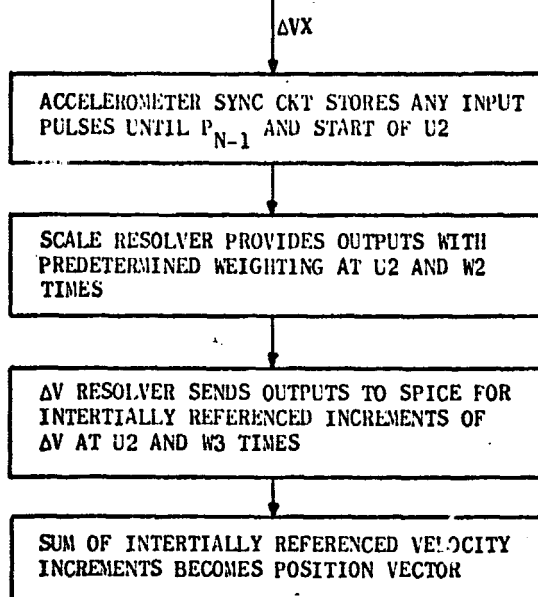


FIG. 14 Accelerometer ΔV input path timing.

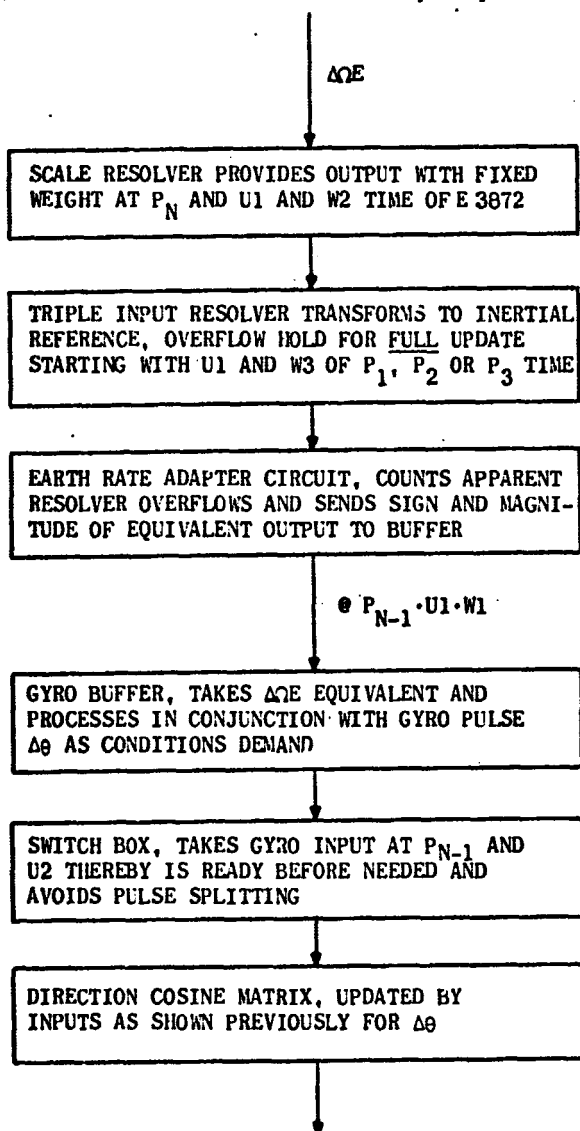


FIG. 15 Earth rate input logic chain timing chart.

as described in the gyro buffer section of the gyro input description (see Fig. 9). From the buffer the pulses are sent to the switch box where the enabling signals required for the appropriate direction cosine matrix update are generated.

Euler Angle Computer and Output Interface. The Euler Angle Computer calculates the angles ψ , ϕ , and θ as described in Sec. 2. When each angle has been found, its value is stored for transfer to SPICE. See Fig. 16 for the block diagram of the entire Euler update cycle.

The key section of the Euler Angle Computer is the comparison logic, in which internally generated direction cosines are compared with a set from the direction cosine computer. Angles ψ and ϕ result from a comparison using the logic shown in Fig. 17. For these two angles the process is as follows:

1. Clear and initialize the two LSB resolvers for ψ or ϕ .
2. Since the equation for the angle being calculated has two terms, $|\Delta R| = C11\Delta S\alpha + C21\Delta C\alpha$ (for the 1st quadrant) it is convenient to sum each term in one LSB resolver. Both LSB and MSB resolvers are capable of an update in every word time of the Euler update cycle. The use of LSB resolver and then an MSB resolver is required to keep the scaling correct. The point of the input gating is to make a typical increment $C11\Delta S\alpha = C11(1)$ instead of $(C11)(2^{-14})$. Since the binary point on these resolvers is effectively between the 15th bit and the 16th bit the shift of binary point at the output of the LSB resolvers becomes $(C11)(2^{-15})$.

3. An initial value is inserted into the MSB resolver. This value is selected from the set of true direction cosines in a manner to be described later. The summed, doubled outputs of the LSB resolvers cause the MSB resolver to be decremented until its content passes zero. The zero crossing is detected by the resolver's overflow flip-flop and this signal halts the angle count being accumulated within the Euler binary-decimal counter (EBD).

The calculation of θ is simpler than that for the other two Euler angles since $C13 = -\sin \theta$, a single term being compared rather than two terms.

The proper positioning of the decimal point where two terms are multiplied requires an LSB resolver. Therefore, in the case of θ , comparison is achieved by counting down the value of $\sin \theta$ (C13) by $\Delta \sin \theta$ increments until $\sin \theta - \Sigma \Delta \sin \theta = 0$. This countdown sets the θ resolver overflow flip-flop and enables setting of the θ comparison flip-flop on its EBD card.

Comparison Logic Inputs: Sine/cosine Generator. This section of the Euler angle computer is composed of four resolvers in positions A16, A17, A18, and A19. The purpose of this generator is to sweep through 90° successively adding increments to the sine register's LSB and subtracting increments from the cosine register (see Fig. 18). The increment is gated by B1 in the MSB part of the registers and therefore represents a change in value of 2^{-15} at every occurrence. The resultant outputs continue to the end of the Euler cycle but are meaningless after the 90° sweep is completed. Outputs that are available to the comparison logic and holding registers are $\sin \alpha$, $\cos \alpha$, $\Delta \sin \alpha$ and $\Delta \cos \alpha$.

Initializing Values. The constants to be used for C11, C12, C13, C23, and C33 for any given Euler angle cycle are stored in the shift registers on card B20. These are loaded simultaneously and immediately before the beginning of an Euler update and are held constant until the next Euler cycle (see Fig. 19).

The value of the constant to be counted down to zero for comparison depends on the trigonometric relationships for the quadrant in question. The terms of the direction cosine matrix that are used in the $\Delta \sin \alpha$ or $\Delta \cos \alpha$ countdown are also a function of the quadrant.

Quadrant Determination. The four quadrants can be determined by examination of the signs of the direction cosine terms in accordance with the following table:

	C11	C12
1st Quadrant	+	+
2nd Quadrant	-	+
3rd Quadrant	-	-
4th Quadrant	+	-

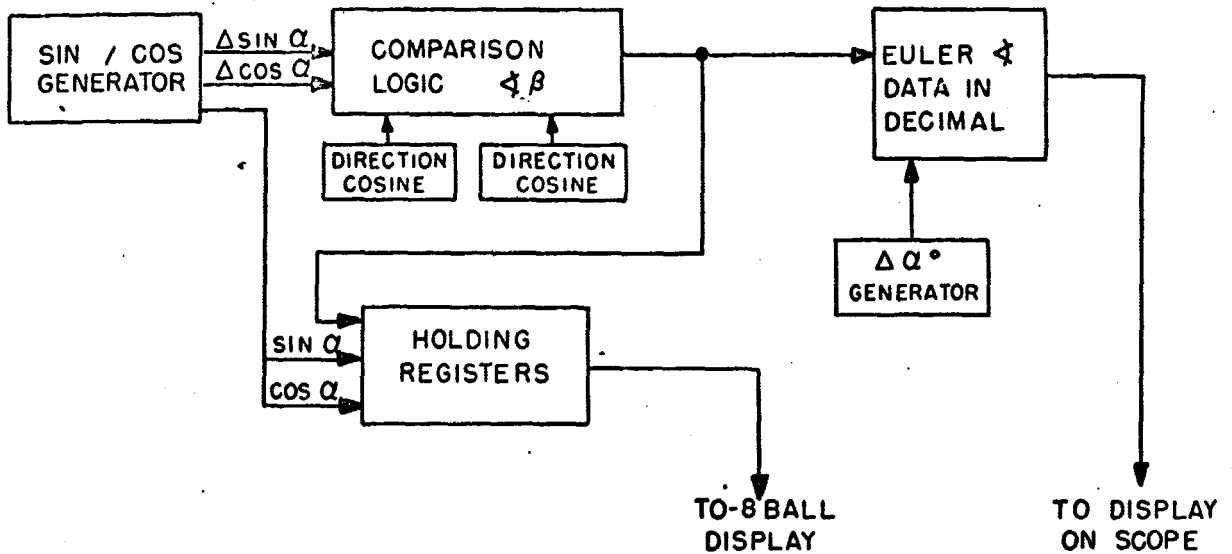


FIG. 16 Detail block diagram - Euler angle computer.

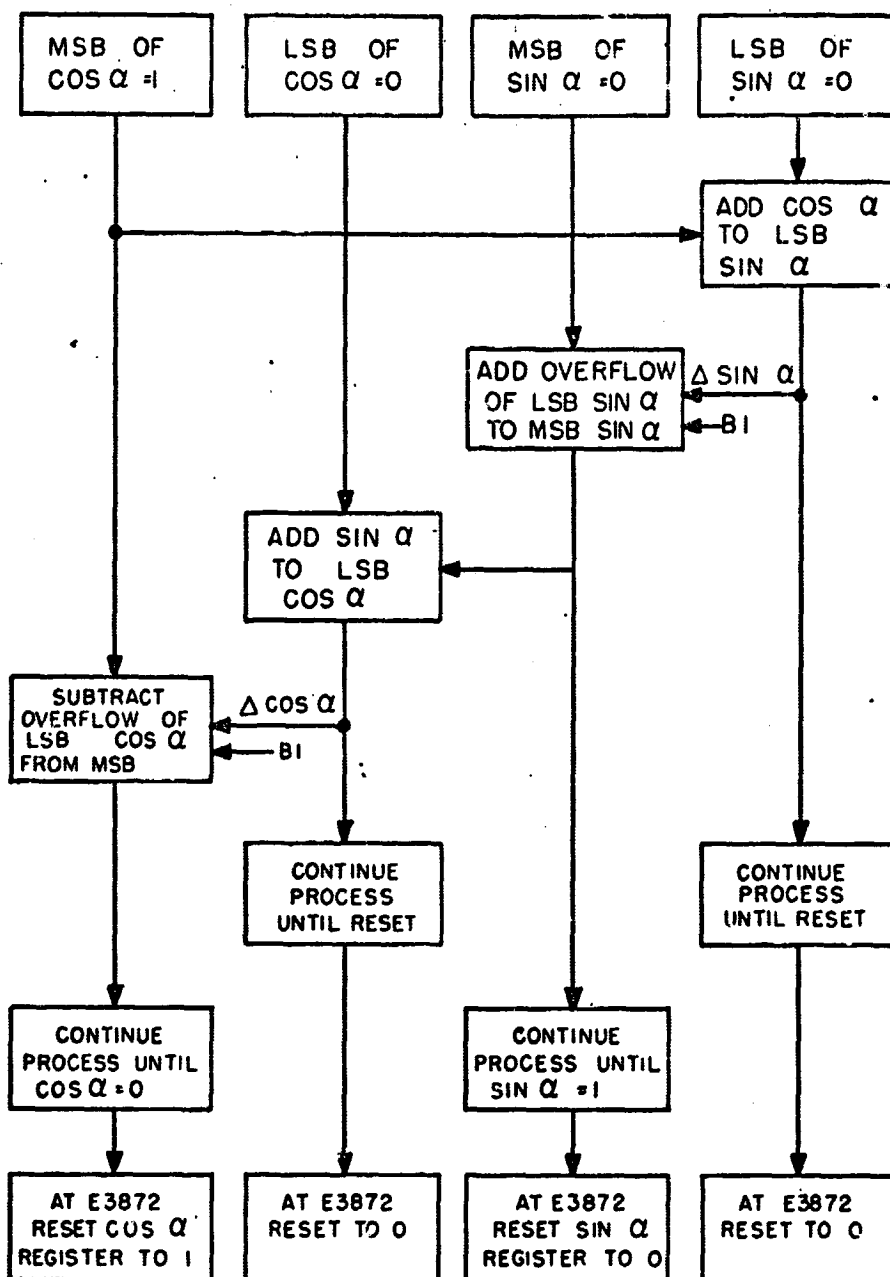
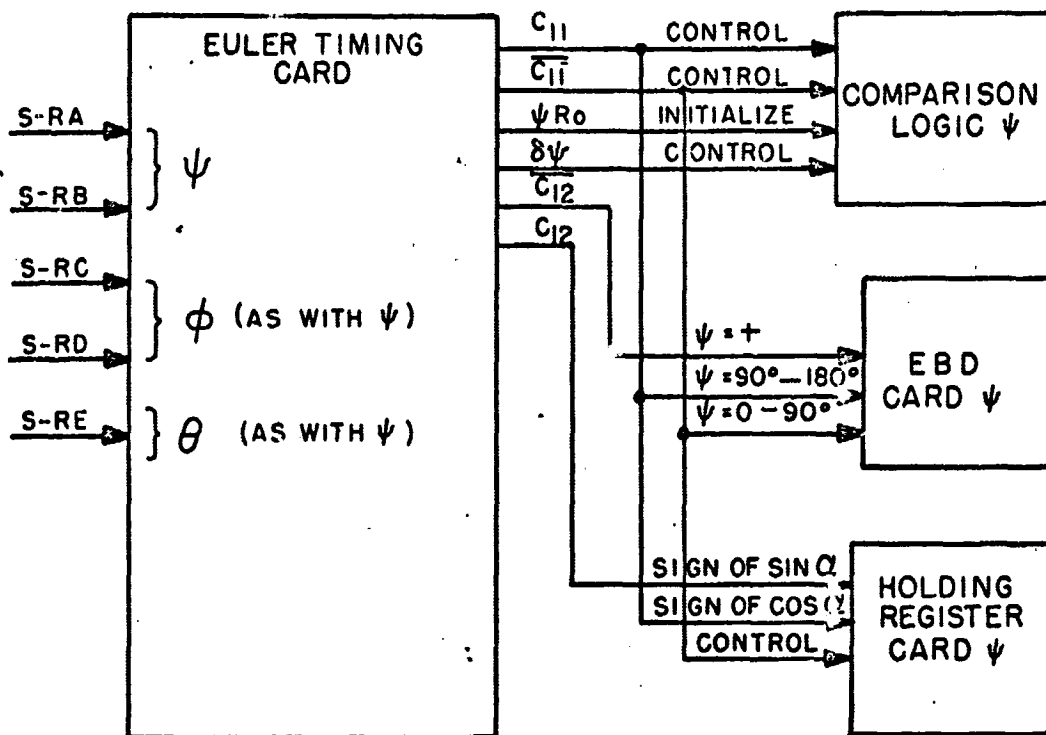


FIG. 18 Sin/cosine generator detail block diagram.



- * USED FOR
1. QUADRANT DETERMINATION
 2. SIGN DETERMINATION
 3. INITIALIZING VALUE DETERMINATION

FIG. 19 Sign and quadrant determination logic.

From this it can be seen that storage of the signs of the five direction cosines used in the Euler angle computer will control the variables between quadrants if gating logic uses the signs to enable the desired values to initiate and control a Euler update cycle.

This use of the signs affects the following areas of the computer:

1. The sign of the values stored on the EBD card of the angles in degrees.
2. The information to preset 90^0 before the update for values of angle in the second and third quadrants.
3. The sign of the binary values of sine and cosine (bit 11) depending on the quadrant that is sent to the Euler holding register cards for use in the eight-ball display.
4. Control of the sine-cosine reversal required for holding register data for quadrant 2 and quadrant 3.
5. Control of the constants used to initialize the comparison logic for the incremental comparison process.
6. Selection of the direction cosine to be multiplied by $\Delta \sin \alpha$ (C11 or C12) and $\Delta \cos \alpha$ (C12 or C11) to achieve proper comparison for second and third quadrant angles.

EBD Card and Display Input. The Euler binary coded decimal card is used to count the increments of angle sent from the Euler scaler from initiation of an Euler update until the required angles are reached (Fig. 20). At the time when the comparison logic overflows to indicate the angle has been reached, a flip-flop on the EBD card is set that stops the $\Delta \alpha^0$ increments from coming in and also freezes the value of the angle's sine and cosine in the eight-ball holding registers. After the completion of the meaningful sin/cos generator run (approximately 180 msec) the value in the counter stages is transferred to the holding register. The data is then available for transfer to the Euler angle display register. It consists of 18 bits in parallel.

Eight-Ball Holding Registers and Output Interface. These holding registers are used to store the values of $\sin \alpha$ and $\cos \alpha$ for each Euler angle for transfer to the eight-ball display unit (Fig. 21). During the Euler cycle the successive values for $\sin \alpha$ and $\cos \alpha$ are shifted through the holding registers. When the comparison is made the ψ , ϕ , or θ gate flip-flop on the EBD card terminates further update of its respective holding register.

After the 90° run of the $\sin/\cos$ generator is completed the interface signal EBW is sent to SPICE. During the next 20 msec the eight-ball unit can shift the 1-bit values (sign plus 10 binary bits) of sine and cosine of all three angles simultaneously. The least significant bit appears first and logical levels are 0 and +5 volts. Interface labeling is SNEY and CSEY for ψ , SNEY and CSEY for ϕ , SNEZ and CSEZ for θ .

CRT Display. A CRT character display is used to display the Euler angles and the contents of the direction cosine matrix. The characters are formed using a 4×6 dot matrix. The character set includes the decimal numerals, a minus sign, a decimal point and a blank. Four lines of 24 characters each are displayed. The display is refreshed at the rate of 51 frames per second.

The top line of the display always contains the three Euler angles (roll, pitch and yaw). The angles are displayed in decimal degrees to the closest 0.01 degrees. The lower three lines of the display are used for the direction cosine matrix. Three six-character octal words are displayed on each line to form a 3×3 matrix. The DISPLAY MODE switch controls whichever elements of the direction cosine matrix are displayed. When positions C1, C2 or C3 are selected, column 1, column 2 or column 3 of the direction cosine matrix are displayed to the full 48-bit precision. When the ALL position is selected, the nine direction cosines are displayed to 16-bit precision.

The block diagram of the CRT display is shown in Fig. 22. The display counter generates the timing signals and drives the horizontal and vertical D/A converters for beam positioning. The Euler angle data is taken from the Euler holding registers in BCD format. The direction cosine data is taken directly from the accumulators and is then formatted to provide octal characters. The character which is being displayed gates the appropriate pulse train from the character generator as the Z-axis signal to the CRT.

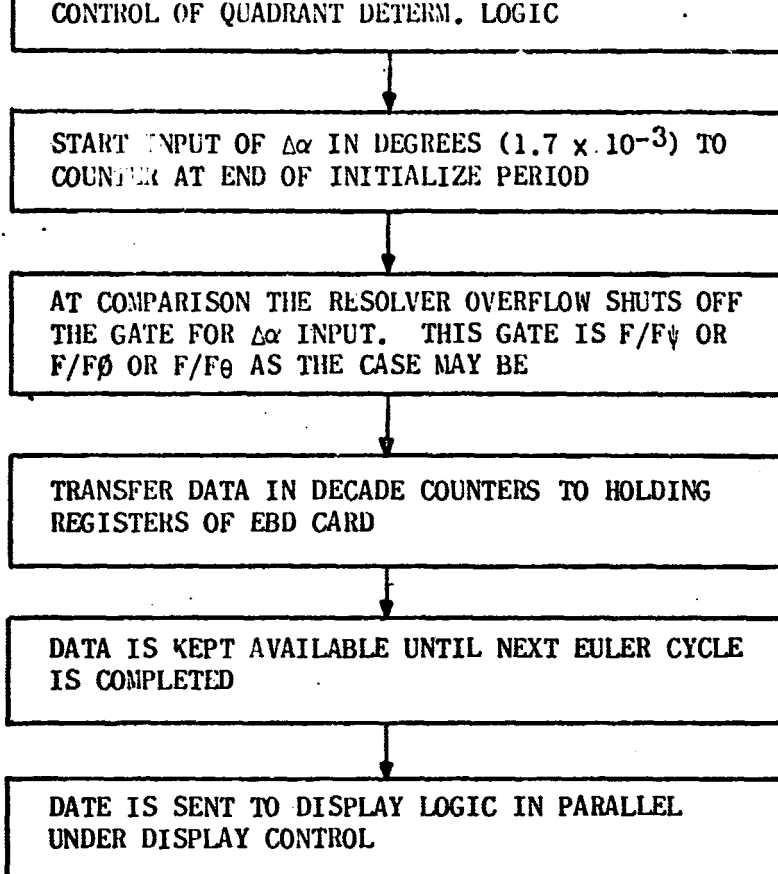


FIG. 20 Euler angle decimal display logic timing chart.

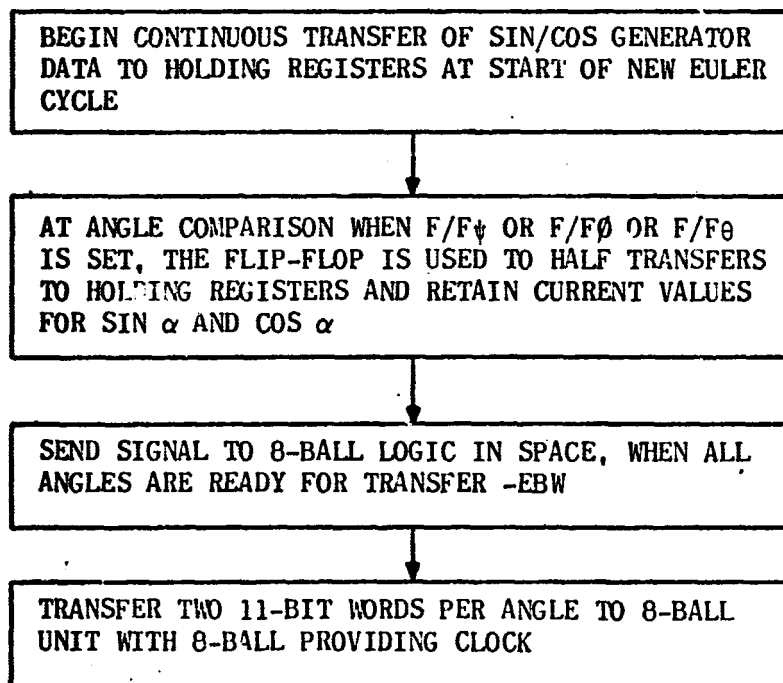


FIG. 21 Eight-ball holding registers timing chart.

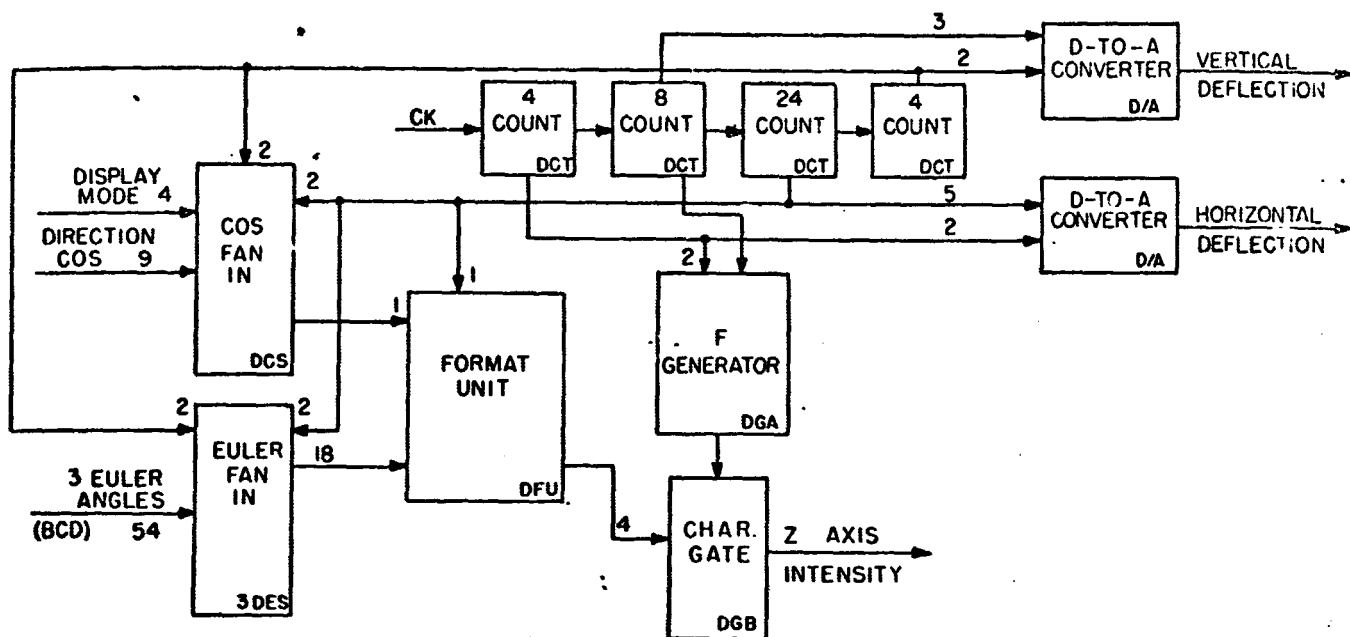


FIG. 22 CRT display block diagram.

Paper Tape Output. The block diagram of the tape output logic is shown in Fig. 23. The data is read out of the computer in a fixed format in ASCII code. The first output character is a "T" to denote the start of a record. The output of a real time clock is then transmitted next to identify the time of the record. The nine direction cosines are then transmitted with the full 48-bit precision. Finally, the accumulated, resolved velocity increments for the three-axes are transmitted.

At the beginning of a record, the contents of the 9 direction cosine accumulators and the three resolvers, are transferred to holding registers. This allows the output record to show the state of the computer at an instant of time. The three resolvers are reset to $1/2$ maximum value when their contents are transferred to the holding registers.

The contents of the real time clock and of the holding registers are then converted to ASCII code and transmitted to the tape unit. The conversion and formatting are controlled by the character control and word control shift registers. Flexowriter control characters such as line feed, space and carriage return are generated and placed on the tape. This allows a meaningful listing of the tapes to be obtained on a ASCII flexowriter without any further data reduction.

The tape output controls are located on the computer panel. The PUNCH RATE switch selects the output rate to be 15, 30 or 60 characters per second. The PUNCH MODE selects the output of a single record or a continuous output. In the CONTINUE position, records are continually punched at the rate selected by the PUNCH RATE switch. In the SINGLE position, one record is punched when the SINGLE RECORD button is pressed. A ground level applied to pin g of the SPICE/SIMU connector has the same effect as pressing the SINGLE RECORD switch. This signal can be used to obtain records at fixed time intervals or when the platform passes through a reference point.

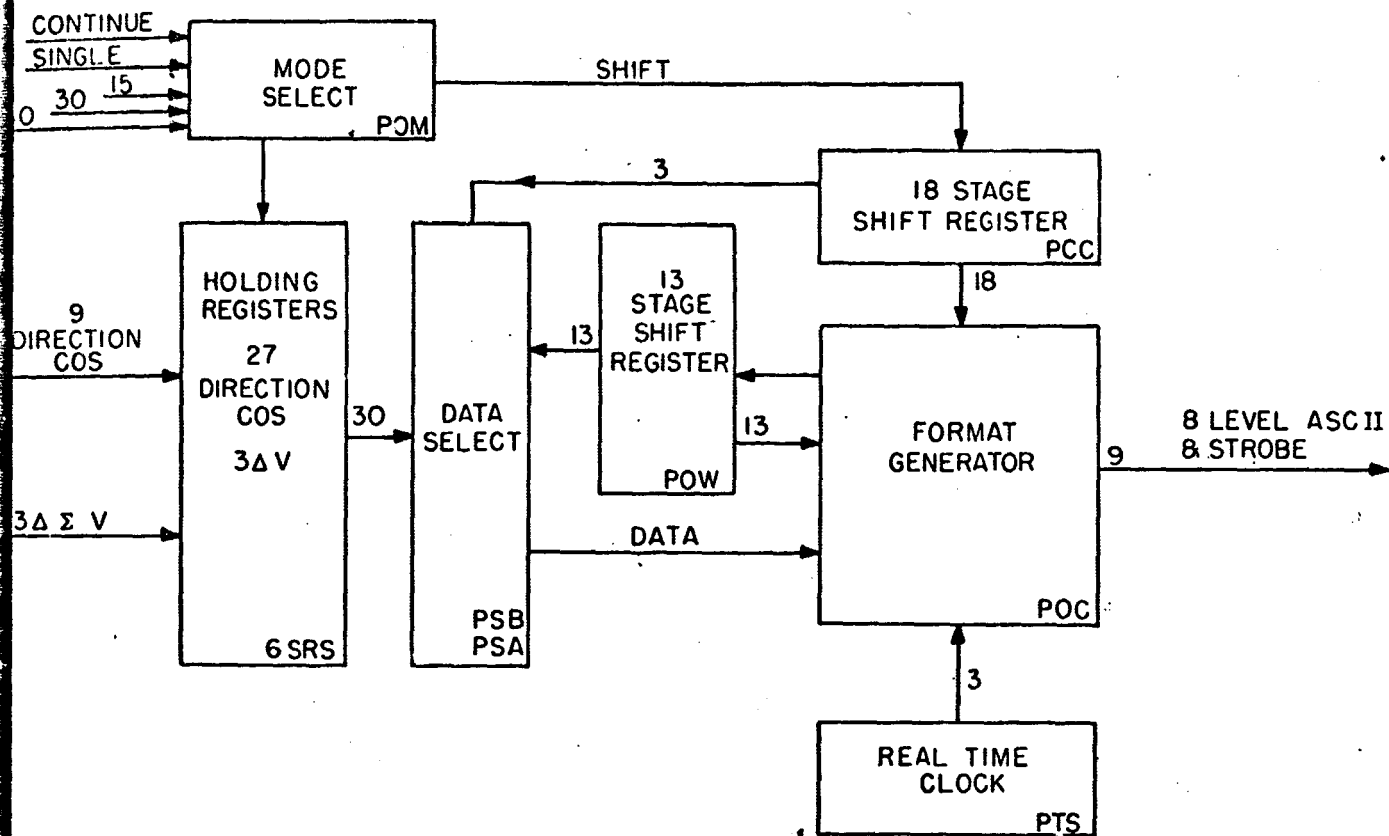


FIG. 23 Tape output block diagram.

SECTION 4

COMPUTER OPERATIONS

Initial Manual Operating Instructions for Strapdown Transformation Computer

1. Plug in power cord to 110 V - 60 Hz, and turn power and scope power to "ON".
2. Check to see that fans are operating..
3. Check that panel lights are ON.
4. Place in "STOP" condition.
5. Ensure that clock switch is on "INTERNAL".
6. Put "COMPUTER MODE SWITCH" to "DIAGONAL" position.
7. Press "LOAD".
8. Place "COMPUTER MODE SWITCH" in "MANUAL" position.
9. Enter 3,3 (0011,0011) into "ADDRESS" switches.
10. Enter 013142₈ (0,001,011,001,100,010₂) into "DATA" switches.
11. Press "LOAD". This sets Euler counting scale factor, which should appear in the "DATA" lights.
12. CRT display should now read

00.00	00.00	00.00
040000	000000	000000
000000	040000	000000
000000	000000	040000

with "COSINE DISPLAY MODE" switch in the "ALL" position.

13. Direction cosines may be set to any desired values by placing value in the "DATA" switch register, addressing the direction cosine via the address register, placing the computer in the "MANUAL" mode, and pressing load. Note that machine scaling is such that a value of unity in a direction cosine is given by 040000₈ or 0100000000000000₂. Two's complement negation is utilized. Register addressing is given by Table 2.

14. In order to register gyro and accelerometer inputs, values must be set into their respective scaling registers. This is done by addressing the proper register (see attached table) and inserting a constant via the "MANUAL", "LOAD" route. The same holds for earth rate.

Input Limits. Gyro and accelerometer inputs are sampled at a rate of 17.361 kHz. This figure serves, therefore, as the upper limit on input rates from the sensors. If gyro scaling is set so that each gyro pulse is equivalent to 2^{-15} radians, the upper limit on angular velocity about each axis (independent of the other axes) is 0.530 radians/sec or about 30 degrees/sec. Other scale settings produce proportionate limits.

Gyro and Accelerometer Scale. It is necessary to place scale factors in the gyro and accelerometer scale factor shift registers. The addresses of these shift registers are shown on the address list. The maximum positive scale factor that can be placed in one of these shift registers is $1-2^{-15}$ ($0\ 111\ 111\ 111\ 111\ 111_2$). The maximum negative value is -1 ($1\ 000\ 000\ 000\ 000\ 000_2$). If a gyro pulse has magnitude $2^{-16} \theta\ 2^{-15}$, the gyro scale factor S should be chosen such that $\theta/S = 2^{-15}$ radians. The choice of accelerometer scale factors is arbitrary, the single constraint being that accelerometer scale factors be chosen to equalize the effective magnitudes of the three accelerometer input pulses.

Euler Scale. The Euler angle scale factor must be initialized each time the computer is turned on in order to provide the proper readings of displayed Euler angle. The shift register which contains this scale factor is SR33 (address 3,3) and the correct value of the scale factor is 013142_8 or $0\ 001\ 011\ 001\ 100\ 010_2$.

Earth Rate Components. The three components of earth rate correction must be entered into shift registers ES_1 , ES_2 , and ES_3 . The proper value for each component is the cosine of the angle between the earth's polar axis multiplied by 0.5315136_{10} .

Tape Input. The data input tapes must use ASCII code. The only characters recognized by the computer are A and 0 to 9. The normal format is AXXYYYYYY where XX is the two character decimal address and YYYYYY is the data in octal. A97177777 would load all ONES into register 97. A97000001

would load a ONE in the least significant bit of register 97. Spaces, commas, line feeds and other characters may be included on the tape to simplify the preparation and listings of input tapes. Other examples of valid formats are:

```
A 97177777  
A 97 177777  
A 97D177777  
A 97;177777  
ADD97CONT 177777
```

The paper tape input is enabled by setting the MODE switch to the READER position. The computer then sends a ready-to-read signal to SPICE and is ready to accept data.

Tape Output. The contents of the direction cosine matrix and the accumulated velocity increments can be dumped onto tape as the computer is operating. Buffer registers are provided so that the data represents the state of the computer at an instant in time. The output rate is selected as 15, 30 or 60 characters per second by the PUNCH RATE switch. The PUNCH MODE switch in the CONTINUE position causes the computer to continually punch data. The SINGLE position of the PUNCH MODE switch allows a single record to be punched when the SINGLE RECORD switch is pressed. This action can also be controlled by the application of a ground level to the proper pin of the SPICE/SINU connector.

The data is transmitted to the tape unit in ASCII code. The output format is shown in Fig. 24. This figure also shows the listing obtained directly from the tape using an ASCII coded flexowriter. The first line of the listing is the contents of the real time clock in octal. The next three lines contain the direction cosine matrix in octal. The particular values are the contents of the accumulators after they have been diagonalized. The bottom line contains the three velocity counts. The 40000_8 represents a net zero count. Values below 40000_8 represent a net negative count and values above 40000_8 represent a net positive count.

TABLE 2

REGISTER ADDRESS LISTS

rection Cosines

<u>Cosine</u>	<u>Upper Word</u>	<u>Middle Word</u>	<u>Lower Word</u>
C ₁₁	9,1	8,1	7,1
C ₁₂	9,2	8,2	7,2
C ₁₃	9,3	8,3	7,3
C ₂₁	9,4	8,4	7,4
C ₂₂	9,5	8,5	7,5
C ₂₃	9,6	8,6	7,6
C ₃₁	9,7	8,7	7,7
C ₃₂	9,8	8,8	7,8
C ₃₃	9,9	8,9	7,9

resolvers

V ₁	Accumulated velocity, reference axis 1	4,1
V ₂	Accumulated velocity, reference axis 2	4,2
V ₃	Accumulated velocity, reference axis 3	4,3
V ₁	Velocity resolver, reference axis 1	5,1
V ₂	Velocity resolver, reference axis 2	5,2
V ₃	Velocity resolver, reference axis 3	5,3
E ₁	Earth rate resolver, reference axis 1	4,4
E ₂	Earth rate resolver, reference axis 2	4,5
E ₃	Earth rate resolver, reference axis 3	4,6
	Earth rate resolver, vehicle axis x	6,1
	Earth rate resolver, vehicle axis y	6,2
	Earth rate resolver, vehicle axis z	6,3
x	x-accelerometer scale resolver	5,4
y	y-accelerometer scale resolver	5,5
z	z-accelerometer scale resolver	5,6

TABLE 2 (cont.)

<u>Resolvers</u>		<u>Lower Word</u>
R0 _x	x-gyro scale resolver	6,4
R0 _y	y-gyro scale resolver	6,5
R0 _z	z-gyro scale resolver	6,6
R1	Euler sin, Y-register	4,7*
R2	Euler sin, R-register	4,8*
R3	Euler cos, Y-register	4,9*
R4	Euler cos, R-register	5,7*
R7	Euler comparator, LSB ↓	5,8*
R8	Euler comparator, LSB ↓	5,9*
R9	Euler comparator, MSB ↓	6,7*
R10	Euler comparator, LSB ∅	6,8*
R11	Euler comparator, LSB ∅	6,9*
R12	Euler comparator, MSB ∅	2,4*
R13	Euler comparator, θ	2,5*
R14	Euler scale resolver	2,6*
<u>Shift Registers</u>		
AS ₁	Accelerometer scale factor, x-axis	1,1
AS ₂	Accelerometer scale factor, y-axis	1,2
AS ₃	Accelerometer scale factor, z-axis	1,3
GS ₁	Gyro scale factor, x-axis	0,1
GS ₂	Gyro scale factor, y-axis	0,2
GS ₃	Gyro scale factor, z-axis	0,3
ES ₁	Earth rate component along reference axis 1	2,1
ES ₂	Earth rate component along reference axis 2	2,2
ES ₃	Earth rate component along reference axis 3	2,3
SR31	Unused shift register	3,1
SR32	Unused shift register	3,2
SR33	Euler angle scale factor	3,3

TABLE 2 (cont.)

<u>Shift Registers</u>		<u>Lower Word</u>
U1	Euler storage of C_{11}	0,4
U2	Euler storage of C_{12}	0,5
U3	Euler storage of C_{23}	0,6
U4	Euler storage of C_{33}	1,4
U5	Euler storage of C_{13}	1,5
U6	Unused shift register	1,6

* Units cannot be initialized.

Real time T , 5 octal characters, carriage return, line feed

C ₁₁	16	octal	characters,	space
C ₁₂	"	"	"	, space
C ₁₃	"	"	"	, carriage return, line feed
C ₂₁	"	"	"	, space
C ₂₂	"	"	"	, space
C ₂₃	"	"	"	, carriage return, line feed
C ₃₁	"	"	"	, space
C ₃₂	"	"	"	, space
C ₃₃	"	"	"	, carriage return, line feed
V _X	5	"	"	, space
V _Y	5	"	"	, space
V _Z	5	"	"	, carriage return, line feed

Listed Output Tape

T37521		
2000000000040000	0000000000040000	0000000000040000
0000000000040000	2000000000040000	0000000000040000
0000000000040000	0000000000040000	2000000000040000
40000 40000 40000		

FIG. 24 Tape output format.

APPENDIX A

A Method for Updating Direction Cosines in a Strap-Down Inertial Guidance System