AN ELECTRICAL NAVIGATION COMPUTER

By

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PREFACE

For many years the navigator has been the work horse of the Air Force. While the pilot sits and watches "George", the autopilot, fly the airplane the navigator is slaving in his cubby hole. As speed and range grow greater his problems are intensified. The tools that the navigator uses have not kept pace with the rapid advance of aerial technology. One of his prime needs is a fast accurate method for making celestial calculations.

The computer presented in this study is an attempt to supply the basic design of a computer which will solve the navigators celestial problems quickly and accurately. No attempt has been made to present a "finished article", one which the navigator could pick up and use tomorrow, but is rather a study of a basic design which could be refined for his use.

It will probably be noted, that explanations of astronomical and mathematical phenomena are often discussed in a very non-technical fashion. It was felt that the fine points of these subjects were of no consequence in the immediate problem, and would only tend to add redundance to the picture. The assumptions made are those generally accepted in the study of aerial navigation.

Indebtedness is acknowledged to Professor Paul McCollum whose valuable guidance and encouragement throughout the construction of the model and the writing of this study were of invaluable aid; and to Mr. Glenn Stotts who helped immeasurably in being able to produce needed parts and technical assistance at crucial times during construction of the model. I wish also to thank Professors Caskey and Mendenhall of the Oklahoma State University mathematics department for their aid in the development of the basic equations. Gratitude is also expressed for the many expressions of interest, and suggestions, offered by the members of the Electrical Engineering Department, especially the comments and suggestions made by Dr. H.T. Fristoe.

It is felt that special mention should be made of the valuable assistance afforded by Wright-Field personnel. The T-1 computer used as a basis for this study was loaned by Wright-Field. Most of the vital parts of the model were supplied from surplus stocks made available to me by Wright-Field personnel.

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CHAPTER I

THE REQUIREMENT

Ever since the first man ventured any appreciable distance from his home cave he has needed some method of finding his way home again or finding his way back to that bountiful fishing stream. At first he provided his own trail by dropping pebbles or breaking branches. When the hunters that lived near large bodies of water decided that it was easier to ride in a boat than to scramble through briar thickets along the shore, a new method of finding their way was needed, and their eyes turned toward the heavens.

The modern specialist had his counterpart in the prehistoric man who by his training, skill, and pure instinct could look at the pattern of the stars and unerringly point the way. Anytime man wished to travel great distances by land or sea this specialist was in great demand. His skill was so revered that he was often the chief or leader of his tribe. Man's insatiable desire to travel and conquer new worlds soon made the demands for this talent greater than the supply and the task fell on lesser men, men who knew that the stars stayed in their same relative position but they needed props to aid them on their way. Because of this need the first navigation instruments were invented.

It was soon apparent that the bright lights of the sky seemed to rotate around one of their dimmer brothers. Of all the stars in the sky only one seemed to always stand still, and they called it Polaris, the pole star. The early mariner soon learned that if he sailed his ship directly toward Polaris the star seemed to rise in the sky. When it had risen to a certain height, say to the first yardarm or to the top of the mast he needed only to turn to the right or left, keep it at this height, and he would sail to his intended destination. Soon man's ingenuity developed more accurate devises. One clever fellow found that if he put marks on a stick and held the stick at arms length with the bottom mark on the horizon he could make the other marks represent the latitude of any port that he desired. He didn't have to move from the Captain's bridge to take a sight at his friendly guiding light no matter what direction he was sailing. In the Bishop Museum in Honolulu is preserved the Sacred Calabash. This ancient sextant was used by the early Hawaiians to find their way home from the Island of Tahiti. It was found that the angle measured between sighting holes in this gourd was 19° 30' the exact latitude of Hawaii. From these modest beginnings grew our present system of celestial navigation and our vast array of navigation instruments. About 1730, Thomas Godfrey of Philadelphia and Captain Hadley of the British Navy independently invented our first modern sextant. The principle used in both cases was that of projecting on a mirrored eyepiece the images of the horizon and the star with a mechanism for changing and measuring the angle between the pick-up prisms so that the two could be brought into coincidence on the mirror. With the advent of aerial navigation, a bubble or pendulum has been substituted for the natural horizon but the principle remains the same to this date. The only purpose of any sextant is to measure the angle between the horizon and the observed star. This angle is called the observed altitude or H_o.

In explaining the use of the sextant for position finding, the most used and probably the best method is through the analogy of a flag pole with a long rope tied to the top. If we visualize this flag pole, and assume that a man is holding on to the rope and keeping it taut all the time, we can outline most of the important definitions that we will need. Since we assume the star to be at the top of the pole, the base of the pole where it enters the ground or in other words the point on the earth directly below the star is called the Sub Point. The angle formed by the rope and the ground is the observed altitude, H_o. If the man walks around the base of the pole holding the rope taut he follows a circular path which is called a line of position or LOP. The angle formed at any instant of time between a line drawn from the man to the Sub Point and a line drawn from the Sub Point toward true north is called the Azmith, Z. If the man comes closer to the Sub Point or goes further away, a new H_o is formed: so for any H_o there is only one LOP. Now assume for a moment that the man is uncertain of his position but he has a set of tables which tells him what angle the star and Sub Point will form at different distances from the Sub Point. He would first assume a position which he thought was fairly close to his actual position, and by using the tables he could find the angle he should measure if he were actually at this assumed position. This angle is called the computed altitude, H_c. He would then measure the H_o and find that it varied slightly from the H_c. If the angle were greater than the H_c he would be closer to the Sub Point than he had thought, if the angle were less he would be further away. By applying a correction proportional to the difference between the H_o and H_c he could find the exact LOP that his actual position would fall on. Now, if he were further restricted by having two flag poles and two ropes to hold onto, he would be on two LOP's which coincide at only two places. In actual practice these lines of position are so great in radius that they appear as straight lines on the plotting chart and the redudent position is so far removed, geographically, that there is no question as to which is the actual position.

To complete the list of definitions, we must visualize the lattice work formed by the earthly latitude and longitude lines, projected out into space and inscribed on the celestial sphere. The earth is considered to be at the center of the sphere with all of the stars at the same distance from the center. thus forming a very large hollow sphere containing all of the stars on its inner surface. The very great distances.

to the stars allow this assumption with no measurable error. The lines on the celestial sphere corresponding to the earthly latitude lines are called Declination lines, Dec., while the lines corresponding to the longitude lines are called Hour Circles. As was done with Greenwich on the earth to aid in the measurement of longitude, an arbitrary point on the celestial sphere was selected as a reference for all east and west angular measurements. This point is called the first point of Aries. All east and west angular measurements are made from the Hour Circle passing through this point. At the pole, the angles between the Hour Circles are called Hour Angles. The different Hour Angles that are of the most interest in this study are: The Siderial Hour Angle, SHA, the angle between the first point of Aries and the Hour Circle that goes through the star we are using. Greenwich Hour Angle, GHA, the angle from Greenwich of any subject Hour Circle. Local Hour Angle, LHA, the angle between our longitude and the star. Figure one shows the relative positions of these hour circles.

One additional piece of information which may be needed is the definition of a Great Circle. A Great Circle is the line formed on the surface of a sphere by a plane passed through any two points on the surface of the sphere and its center. When projecting the surface of a sphere on a flat plane the Great Circle appears as a curved line but still represents the shortest distance between two points on the surface of the sphere.

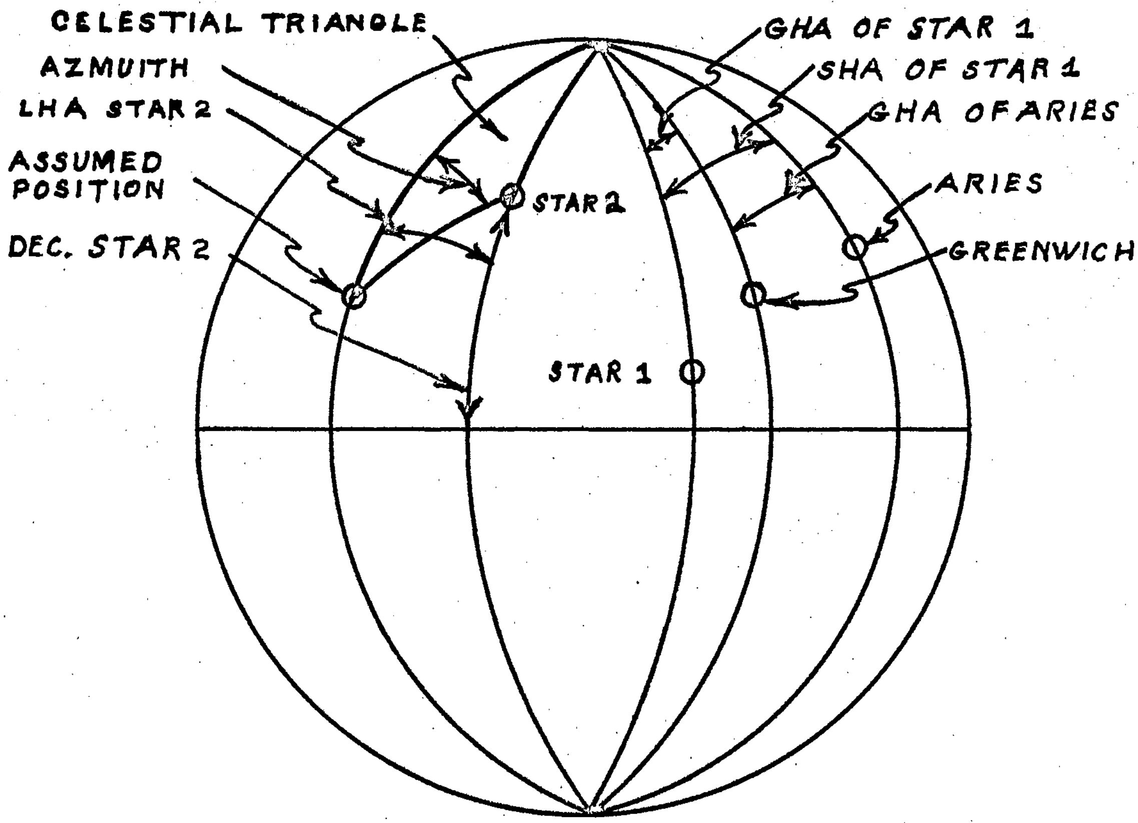


Figure 1. The Celestial Sphere

With the various definitions listed above firmly in mind, let it be explored further how the navigator fixes his position on earth by use of the stars. As was briefly mentioned before, the stars stay in their same position relative to each other, and to the observer on the earth they follow the same path across the sky day in and day out, varying only in the time which they rise above the horizon. It may be well to note here that the above statement is not true of the sun, the moon, and the planets which, due to their closeness to earth, travel a different but predictable path each day throughout the year. Since the stars are fixed in space for all practical purposes, their positions can be described in the celestial sphere by their Dec. and SHA as surely as Chicago or New York can be located by its latitude and longitude. Furthermore, by knowing the GHA of Aries the corresponding GHA and SHA can be combined, thus locating the Sub Point of the star. The triangle formed by the longitude line running through this position, the longitude line running through the Sub Point of the star, and the Great Circle line between this position and the Sub Point, is called the Celestial Triangle. The longitude lines running through the Sub Point and this position are known. What is not known is the length and Z of the Great Circle line joining these two positions. In addition to the information listed before, figure one shows this celestial triangle with its different parts labeled.

All systems and plans for Celestial Navigation are simply different methods for finding these unknown quantities.

Harking back to the flag pole analogy, it is recalled that the unknown distance from the Sub Point was found by measuring the angle of the star above the horizon and comparing it with an angle precomputed from an assumed position. This method lends itself very well to practical application especially since one minute of arc is equal to one nautical mile when measured on the surface of the earth. Most methods employ this principle, but two notable exceptions are the British "Astrograph" and the "Weems Star Charts". Both the "Astrograph" and the "Star Charts" use the principle of projecting or printing the actual path of the Sub Point on a chart and plotting the H_o directly on the chart a measured distance along these Sub Point lines. Of course, the first method used for solving the Celestial Triangle was by straight spherical trigonometric means. This method was very accurate but was unduly complicated and took considerable time to accomplish. At first the time involved was of little consequence since man was only traveling at about fifteen knots, but when the navigator "sprouted wings", time became a prime factor. The "Ageton" method of solution was a step in the right direction. This method consisted mainly of a printed format which labeled each step of the mathematical solution so all that was necessary was to follow the format, putting in the required information, adding or subtracting when it so indicated. In about twenty minutes an answer could be obtained. The first and, as will be seen, the last giant step forward was the "HO" publications. The Hydrographic

Office of the Navy produced thousands of solutions of Celestial Triangles and compiled them in tabular form into books. Using these publications, a person needs only to know the Dec. and LHA of the star and to assume a position. With this information he can go to the tables and extract the H_c and Z. Each of the three major "HO" publications, HO214, HO218, and HO249, are slightly different but are all based on the same principle of tabular information for major celestial bodies which can be used for any assumed position. These "HO" publications, along with "The Air Almanac", have been the corner stone of aerial navigation since before World War II and have remained so until today. From time to time different computers or devices have been presented to lighten the load of the navigator, but one by one they have been discarded for various reasons. One interesting device was the "Astrobine", with which two stars were sighted at the same time, resulting in a marked plug which was placed in a reader device, which in turn gave a distance and Z from the assumed position. The "Astrobine" proved to be quite satisfactory on the ground but was too difficult and too inaccurate to use in an aircraft. Several computers have been devised, but here again difficulty of use and inaccuracy have minimized their value. Of the computers conceived in the past, the T-1 was one of the best. The computer presented in this thesis is an outgrowth of the T-1 computed. A thorough explanation of the T-1 will be found in Chapter 2.

As aircraft have flown faster and faster it has been necessary to develop techniques which save time in celestial computation. In the absence of anything better, the present day navigator still uses the HO publications, but most of his work is done on the ground before take off. Before the mission, the Navigator lays out his intended track and precomputes the H_c for different stars and positions along his route. During flight, he need only stick comparatively close to his preplanned route and timing, and the major portion of his time consuming task is already accomplished. The main difficulties in this plan are in its comparative inflexibility, and the fact that no time or labor is actually saved but simply shifted to a more convenient period. The inflexibility of the present system becomes apparent when deviation from the original plan is required. If there is a last minute change of target, the Navigator is in trouble unless he has plotted courses to cover all eventualities. On standby alert the Navigator must be ready to take off at a moments notice so a constant revision of his plan must be accomplished. Diversion in the air due to enemy action or operational considerations are a constant threat to any precomputed plan. As it stands now, slight deviations from his precomputed plan are possible through correction techniques available. If any major change in plans occurs he must fall back to the old method of thumbing through endless tables. Under the stress of time, enemy action, adverse weather, and many other factors that plague the harried Navigator, it is easy to make simple mistakes like adding two and two and getting five, or skipping down one line as information is extracted from a table. The ultimate objective of the computer designed and presented in this thesis is to give the navigator an accurate H_c and Z in less than thirty seconds, to be simple to use, either on the ground or in the air, to greatly reduce the overall work load of the navigator, to drastically reduce simple addition and subtraction errors, to be independent of changes in flight plan, and to greatly reduce the amount of bulky equipment that the navigator generally must carry with him.

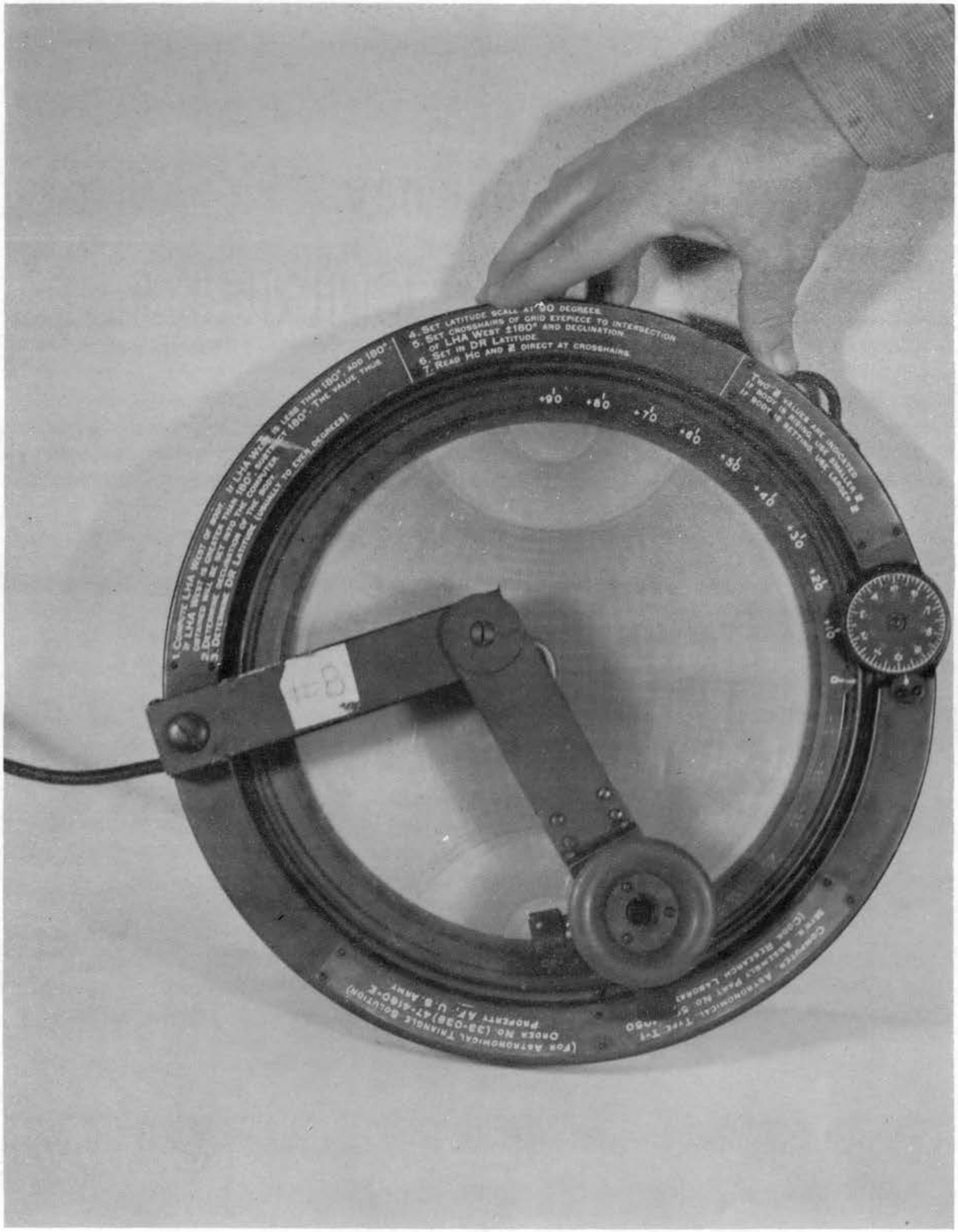
CHAPTER II

THE T-1 COMPUTER

At the end of World War II, representatives from the Wright Patterson Air Force Base, Ohio, entered Germany in search of Luftwaffe equipment which could be used in the further development of the United States Air Force. Among the equipment brought back was two models of what was later called "The T-1 Celestial Navigation Computer". This equipment was a German development of a French idea, and was a devise for obtaining the H_c and Z of a star when the LHA, Dec., and assumed position were set into its mechanism. A photo of the T-1 is shown in Plate I.

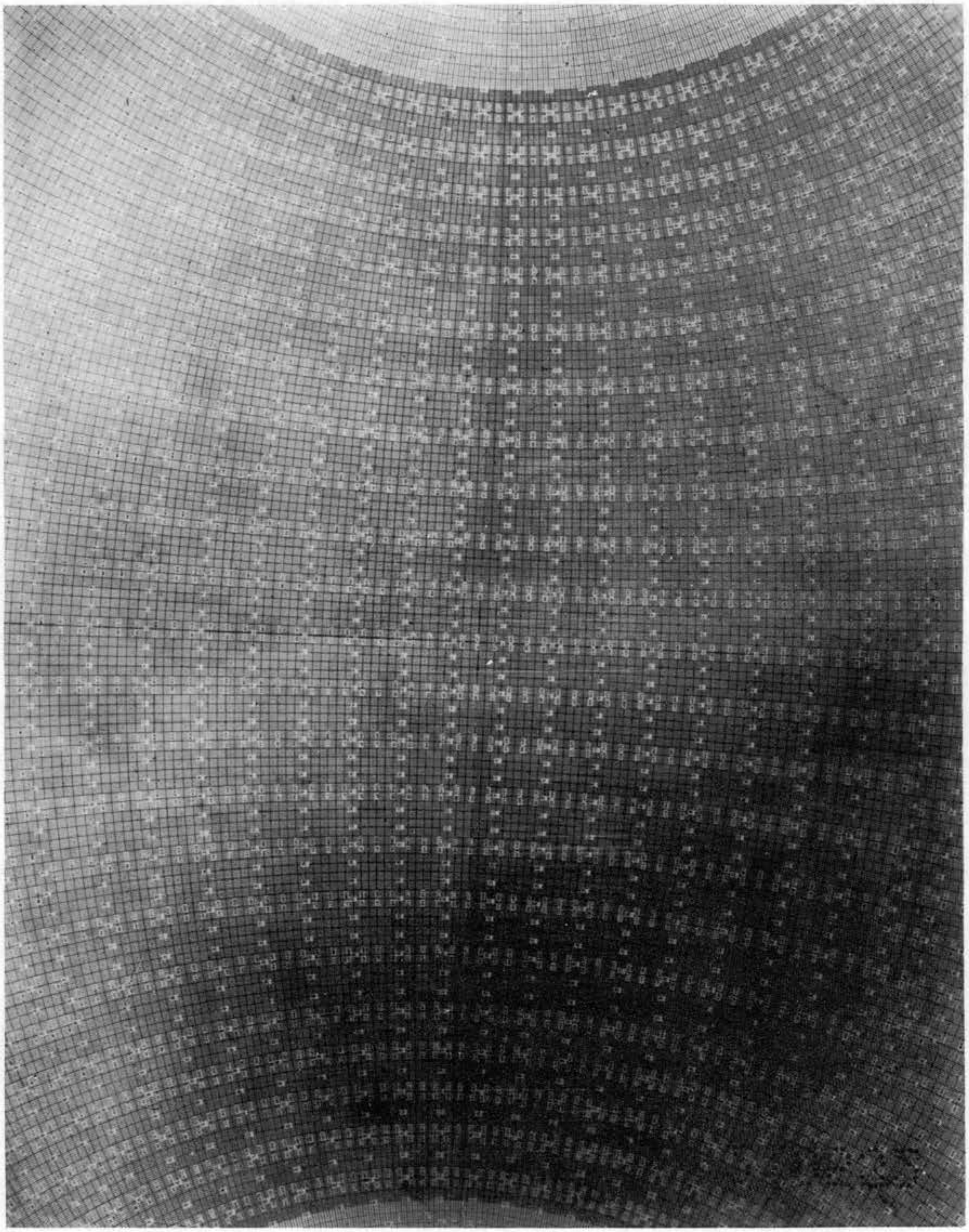
The devise consists of a round glass plate on which a series of vertical and horizontal curved lines are printed. This glass is mounted in a metal ring which can be rotated by a knob at the top of the computer. Above the plate is mounted a flexible arm, on the end of which is a twelve power magnifying lens with adjustable cross hairs. The intersections of the inscribed lines are numbered as illustrated in Plate II. The vertical lines are drawn so that the curvature of the outermost line has a radius equal to the radius of the plate. Lines closer to the center have greater radii, and the line at the center has an infinite

PLATE I



The T-1 Computer

PLATE II

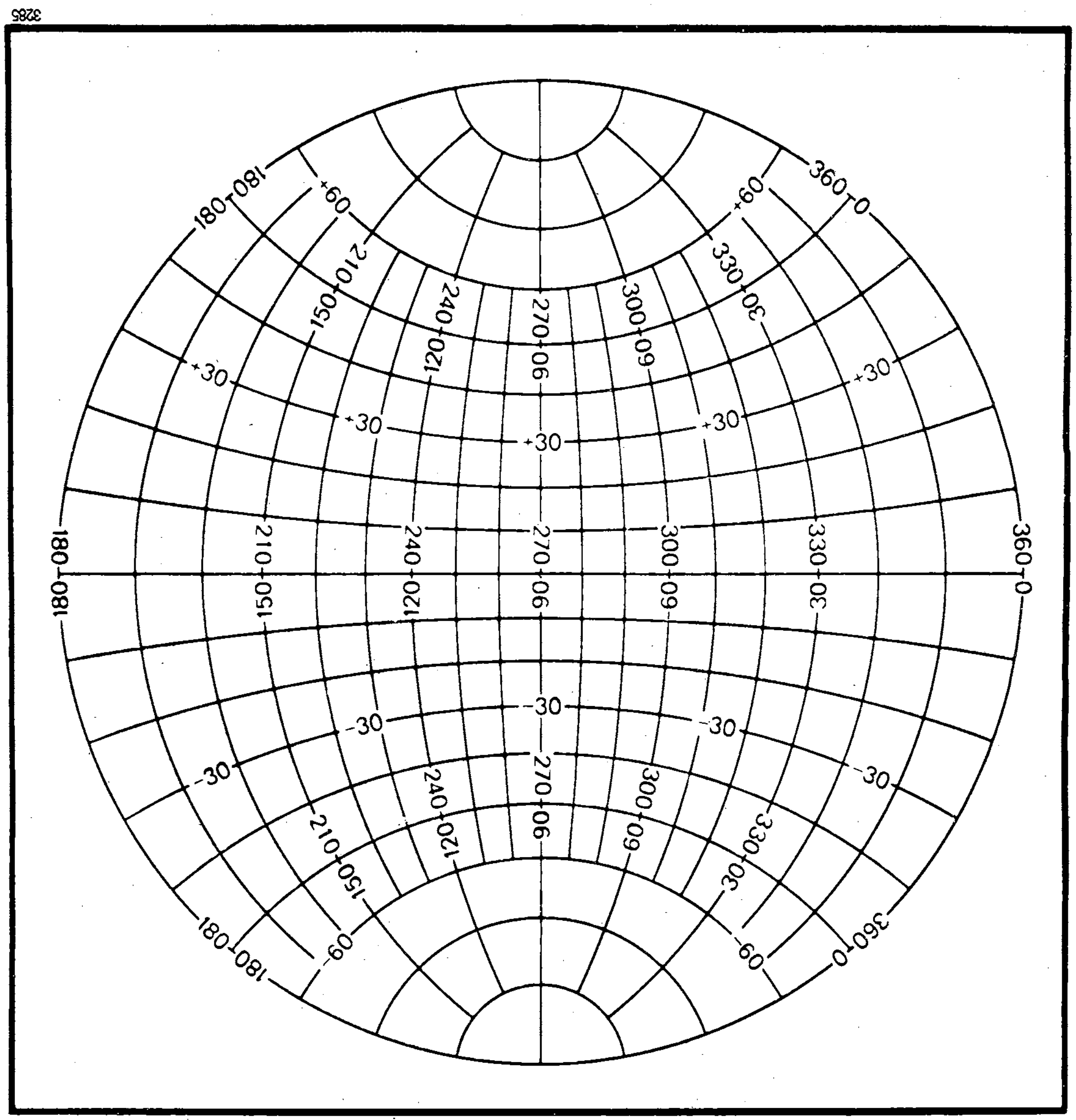


T-1 Computer Plate

radius or in other words the center line is a straight line. The horizontal lines are constructed so that the outermost curve has a radius of zero. This radius increases for lines closer to the center until at the center there is another straight line. A drawing of the lines as they appear on the plate is included as Plate III. A very non-technical explanation of why this configuration of curved lines is used is that this is the way the latitude and longitude lines would appear to an observer stationed in space. If this space observer were to start at a point directly above the equator and travel to a point over the pole always observing the latitude and longitude line immediately surrounding his Sub Point, they would appear as they do on the computer.

To solve the Celestial Triangle problem on the computer the knob at the top of the computer is first set so that 90° is read on the assumed latitude scale which is etched along the side of the mounting rim (the index rotates with the glass plate). With the assumed latitude at 90° the flexible arm in moved so that the LHA of the subject's star is read on the vertical curved lines, and the Dec. is read on the horizontal curved lines. The movable cross hairs in the eyepiece make possible comparatively accurate settings. The plate is then rotated so that the actual assumed latitude is read on the outer rim scale. The cross hairs are then centered on the H_c and Z of the star. The H_c is read from the horizontal curved lines, and the Z from the vertical curved lines. Again, a very non-technical explanation of

PLATE III



Arrangement of Lines on Computer Plate

why this system works, is that if the position in question was actually at the north pole, the H_c would be the same as the GHA of the star, thus establishing a Sub Point. If it is then imagined that the earth is rotated and tilted an amount equal to the assumed position with the celestial sphere held stationary, a new Sub Point is established. The Dec. of this new Sub Point now becomes the actual H_c, and its new GHA becomes the actual Z.[1] Figure 2 demonstrates this idea.

Once again, as has been true with most computers, the T-1 proves to be quite good on the ground, but in the air the flexible arm is hard to adjust, the cross hairs are hard to set accurately and have a tendency to jam. Also the T-1 is difficult to read. Mass manufacture of the computer has been difficult due to the precision required, difficulties with the photo etchings on the plate, and the complexity of the magnifying eyepiece with its associate cross hairs. The computer has never been accepted as a standard Air Force item.

So it is seen that the idea behind the T-1 is good, but practical problems of manufacture, cost, and use, greatly limit its application.

The first attempt to resolve the difficulties of the T-1 was attempted by this author in February 1948. At that

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[1]It could also be as easily visualized that the Celestial Sphere was rotated and tilted while the earth remained stationary.

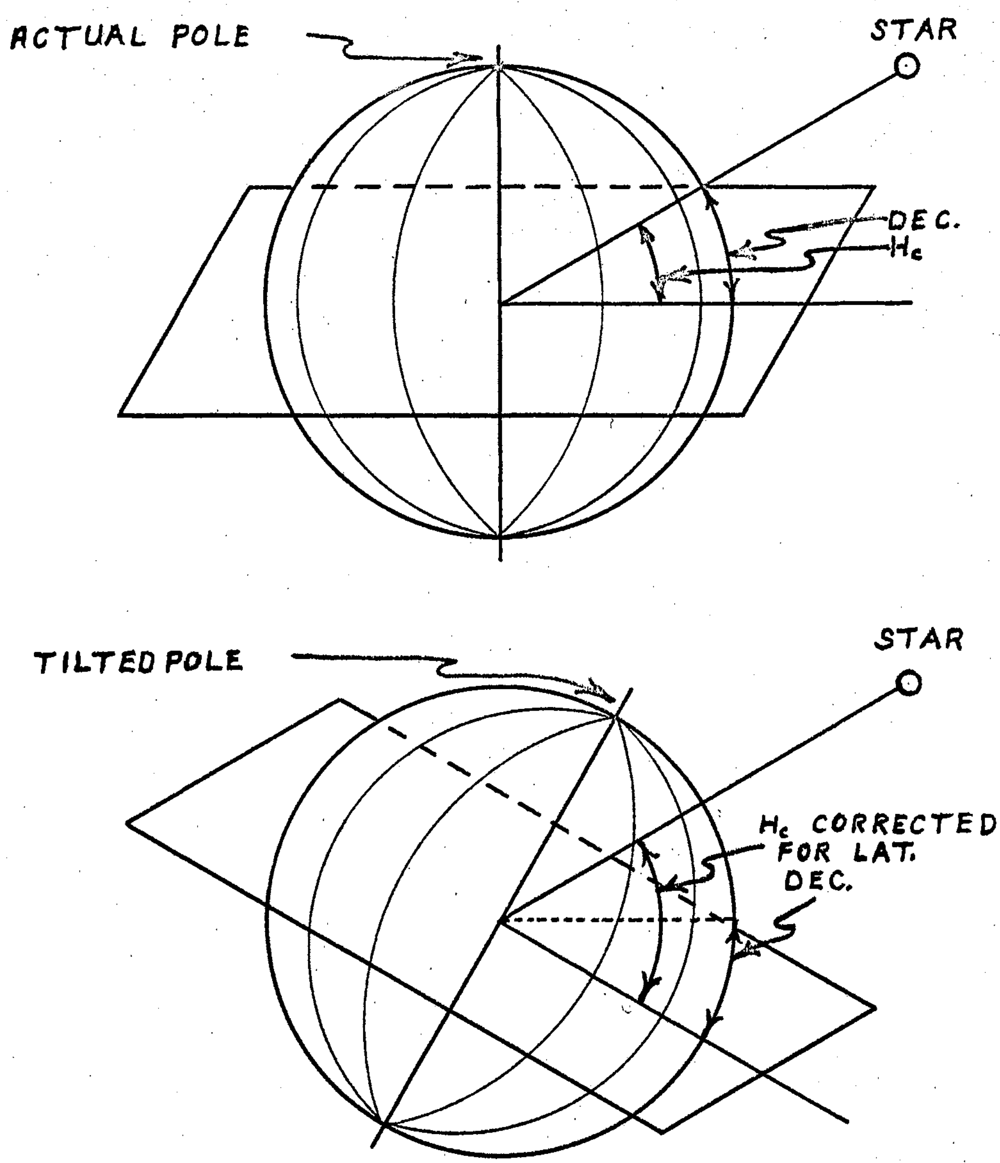

Figure 2. Correction for Assumed Latitude

time an attempt was made to simulate the movement of the eyepiece by means of a series of ball, disk, and roller devices. This work was not carried to a point of evaluation due to the discharge of the author from the service.[2] The problems of the T-1 are here again approached, this time with the application of electronic principles in mind.

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[2]A more complete outline of previous work is included as Appendix A.

CHAPTER III

A NEW APPROACH

The first step in the solution of the subject problem was to obtain the equations for the vertical and horizontal curved lines on the T-1. A complete mathematical development of these equations is found in Appendix B. As may be seen from the development in Appendix B, the equation for the vertical lines is $X^2 - (a^2 - r^2)/a + Y^2 - r^2 = 0$, and for the horizontal lines is $X^2 - (b^2 + r^2)/b + Y^2 + r^2 = 0$. Assuming that r is always unity, $(a^2 - r^2)/a$ is equal to A, and $(b^2 + r^2)/b$ is equal to B. The equations then become $X^2 - AX + Y^2 - 1 = 0$, and $X^2 - BY + Y^2 + 1 = 0$. Figure 3 shows where these values are measured, and that simultaneous solution of the equations results in a specific X and Y for any known "a"(LHA) and "b"(Dec.). Several different methods of solving these simultaneous equations were attempted using analog computer techniques. Straight algebraic solution of the reduced equation required more operational amplifiers than were available. Reduction of the equations by subtraction resulted in an equation which was satisfied by an infinite number of X and Y combinations. Attempts to differentiate and then integrate, or integrate and then differentiate, resulted in losing vital parameters. The final solution,

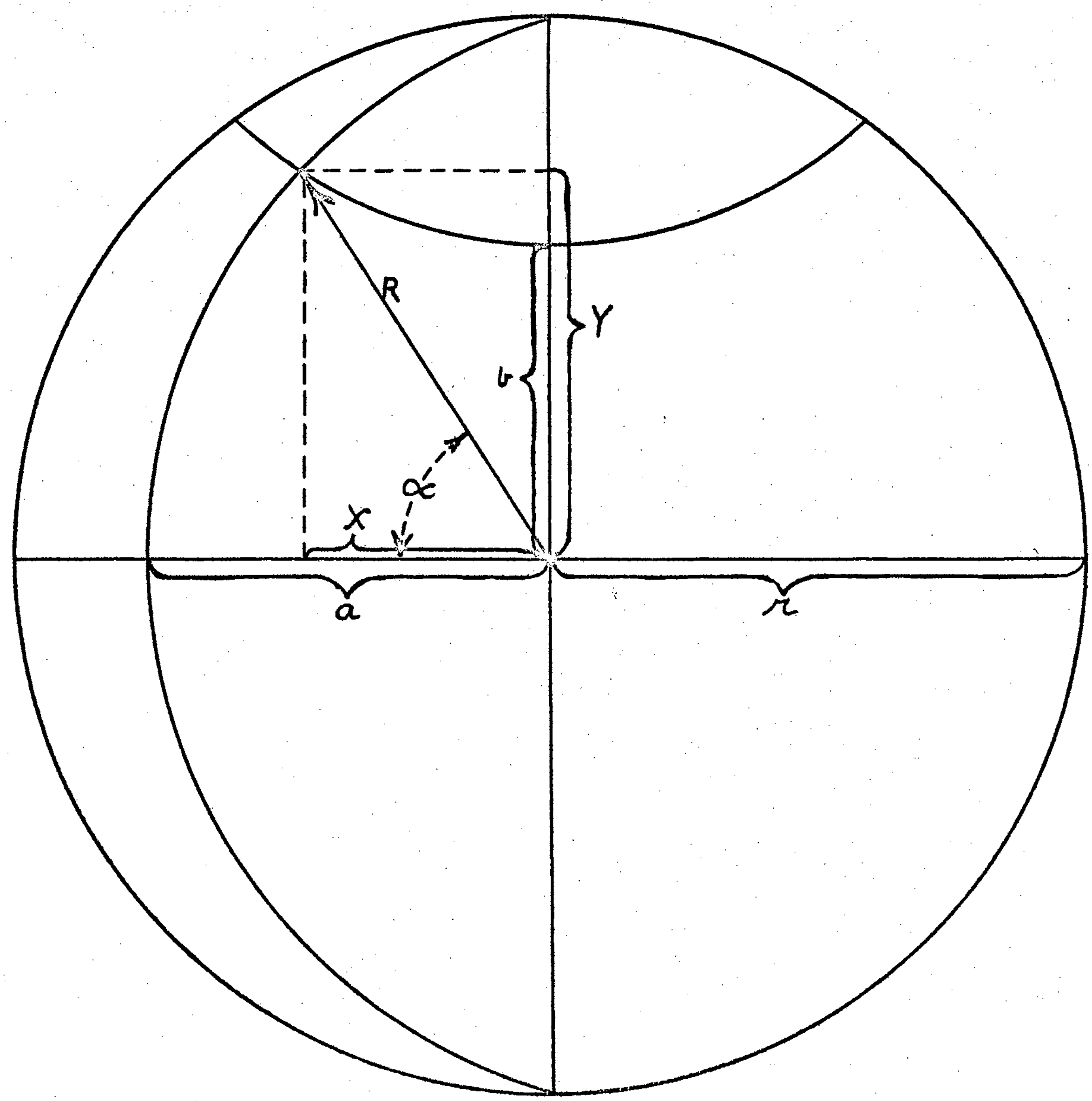

Figure 3. Nomenclature of Basic Equations

which was accepted, incorporated a system of servo-multipliers coupled with voltage divider networks and operational amplifiers. It may be well to note here that although no straightforward analog computer solution was found, it is believed that further study in this area is warranted.

After establishing the basic equations, their solution and the complete solution of the T-1 problem may be divided into five major steps:

1. Setting up the equations and determining X and Y,
2. Vectorizing, or turning the X and Y position into a vector of length R and angle α,
3. Rotating the vector,
4. Quadrant selection,
5. Final answer.

Figure 4 depicts a diagramatic explanation of these five steps.

To solve the original equations, a voltage proportional to each of the equation parameters is applied into a summing amplifier. If the voltages are all correct, the output of the summing amplifier will be zero. If the voltages are not correct, the summing amplifier will have an output proportional to the error involved. This error signal causes a servo motor to turn. The servo motor positions potentiometers which affect the input voltages. The motor will continue to turn until the sum of the input voltages result in a zero error output. If the error is positive, the motor

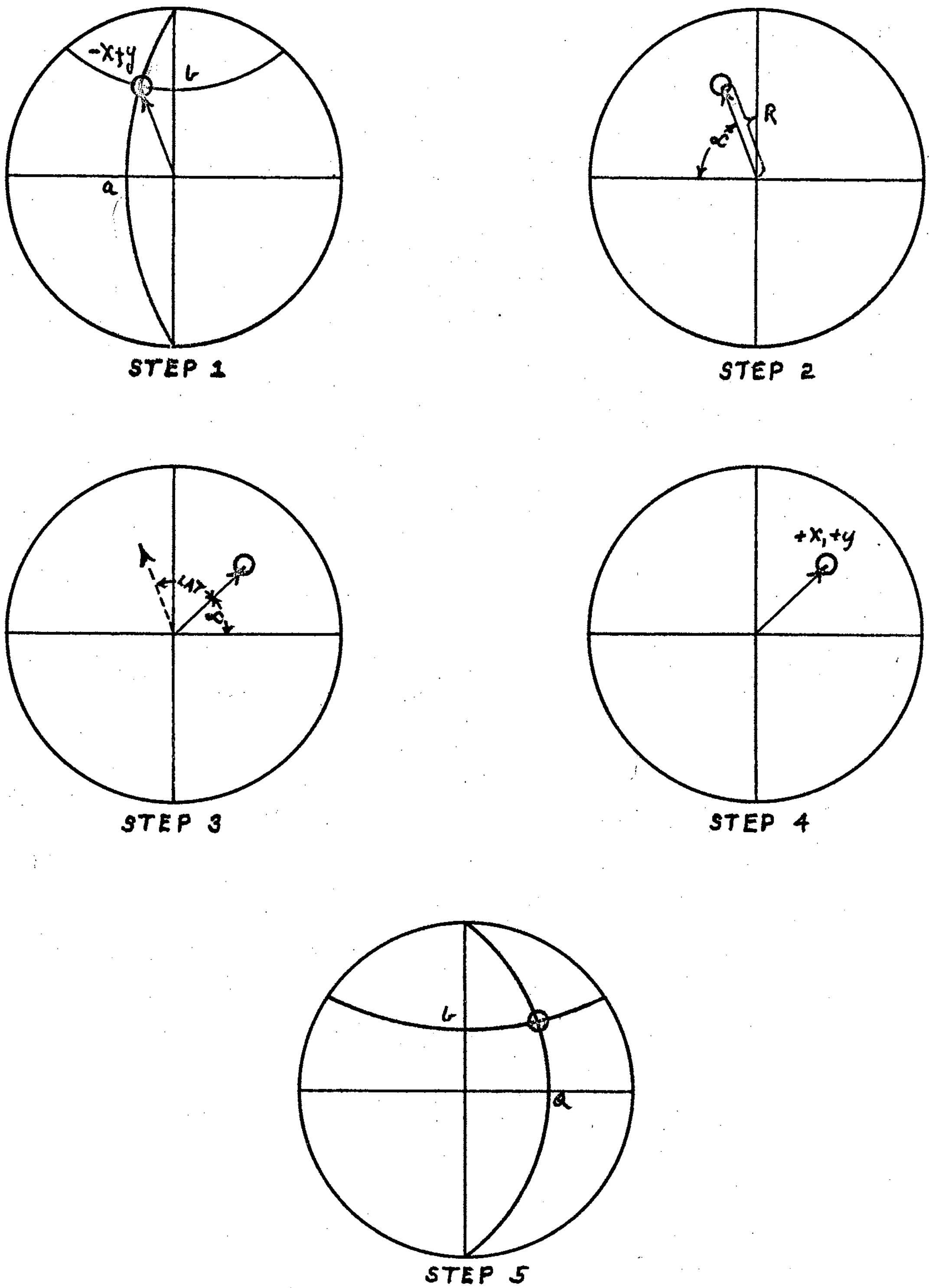

Figure 4. Five Steps of Solution

turns in one direction, and if negative, the motor turns in the opposite direction. Since two equations are involved, two complete systems as described above are needed; one for X and one for Y. X and Y occur in both equations so inner connection between the two is necessary. This inner connection introduces a brief oscillation. Since it is only a few seconds duration, and is an indication of the proper operation of the instrument, this oscillatory period is considered an advantage rather than a disadvantage. Furthermore, it is an indication of low drag in the system. When the motors have come to rest, the potentiometers are in a position relative to the intersection of the lines established by the known A and B, and their output represents X and Y. Voltages representing X, Y, X^2, Y^2, AX, and BY are then available. Figure 5 is a schematic of this portion of the computer.

$X^2 + Y^2 = R^2$, so by adding the X^2 and Y^2 voltages and applying the resultant to a servomultiplier system, as shown in Figure 6, R is obtained. This is the first step in turning the X and Y position into a vector, however, the angle must still be established. The voltage R is applied to a sine-cosine potentiometer (sometimes called a square card potentiometer). From the cosine output of the potentiometer R cosine α is obtained, and from trigonometry it is known that R cosine α is equal to X. R cosine α and -X are then used as inputs to a summing amplifier. When the output of this summing amplifier is anything but zero a motor is caused

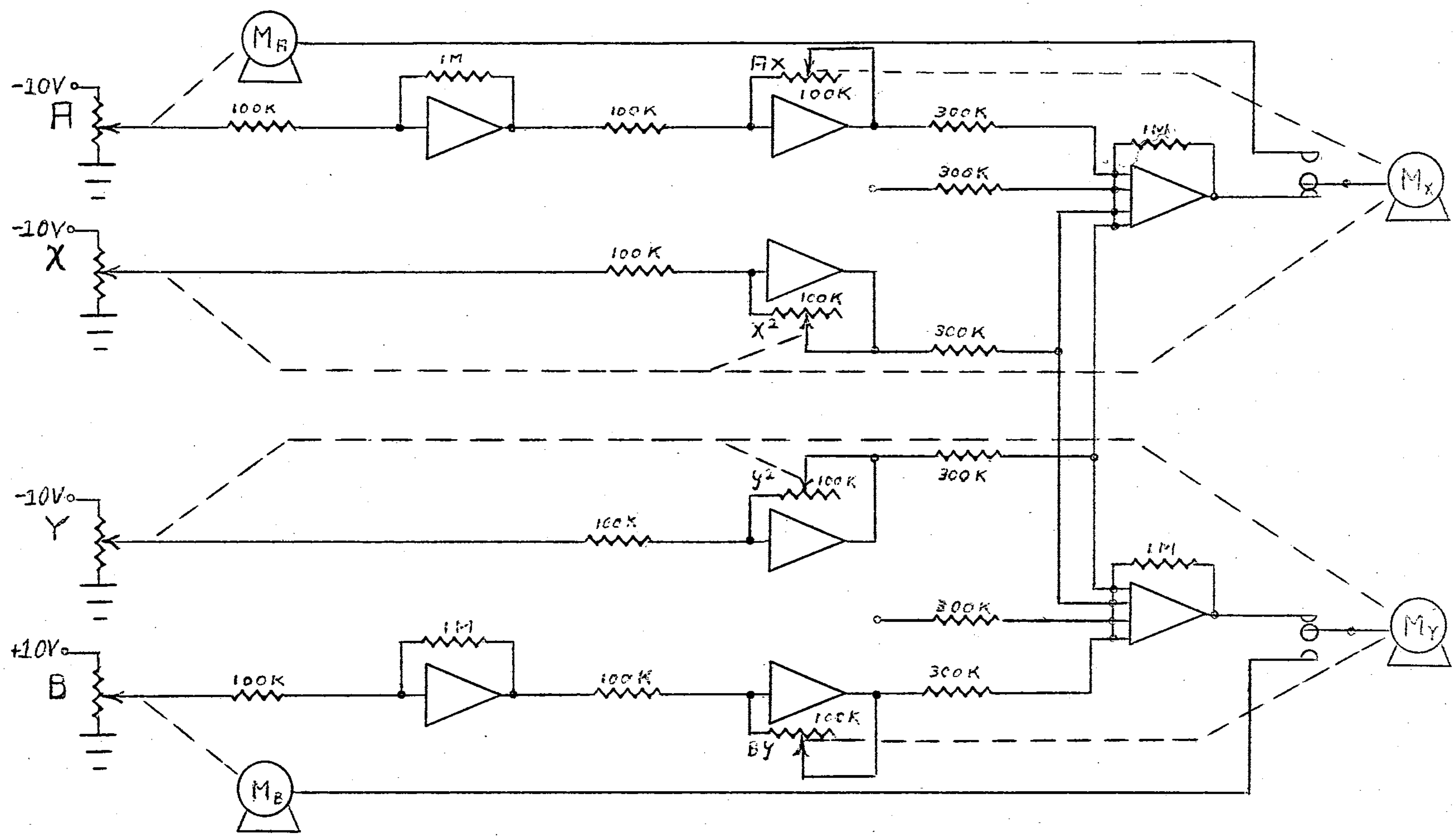

Figure 5. Solving for X and Y

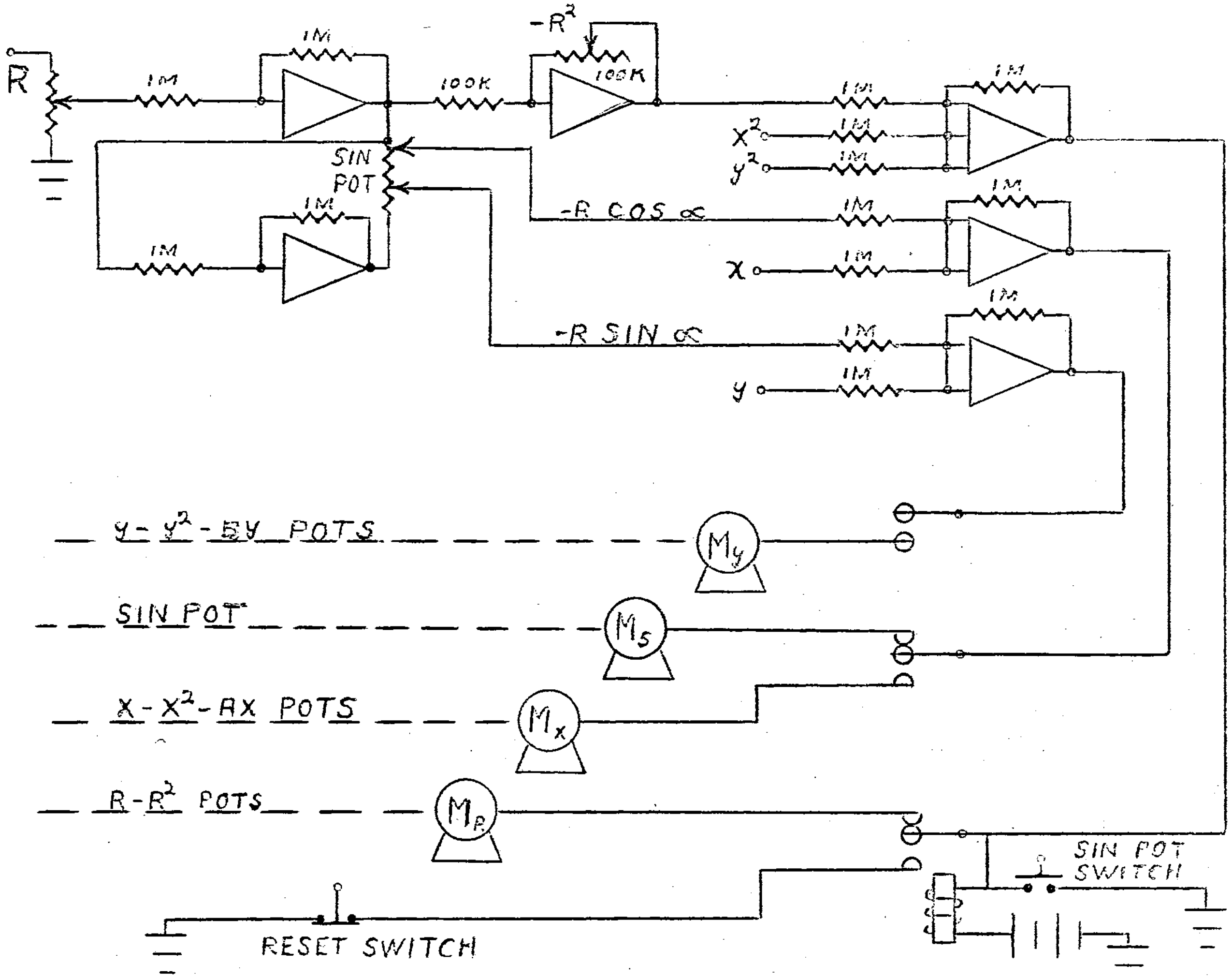

Figure 6. Solving for and Rotating Vector

to turn. This motor rotates the sine-cosine potentiometer until the correct α is established to make R cosine α equal to X. The vector is now established with a length represented as R at an angle of α. Figure 6 shows a complete schematic of the vectorizing operation. If the progress of the electrical solution is referred to the T-1 computer, a point has been reached where the eyepiece has been centered on the LHA and Dec. The next step is to apply the assumed latitude.

On the T-1, the assumed latitude is taken into account by rotating the plate under the eye-piece. In the electrical solution, the vector is rotated an amount equal to the assumed latitude. To simulate the rotation of the vector around the origin, the length, R, must remain the same with only α changing. The drive of the sine-cosine potentiometer is arranged so that the pointer on its indicating dial does not rotate during the vectorizing operation above. When the assumed latitude is set, the geared pointer shaft and the gear on the sine-cosine potentiometer drive are engaged. Engagement of these gears activates a relay. The relay disconnects the motor drive on the R servo multiplier forcing R to remain the same. The above relay also releases the sine-cosine potentiometer from its motor drive allowing free movement of the pointer.[3] (Figure 6) The vector has now been

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[3]A holding relay is provided so that as long as a spring loaded reset button is in the normal position, the relay will remain activated. After the problem is completed, the button is depressed, the relay releases, and the computer is ready for a new problem.

rotated, but R cosine α is no longer equal to the X that is set on the computer.

When the vector is rotated, a new problem presents itself. It is quite possible that the new X and Y lie in a different quadrant than the original X and Y. This problem is solved by providing the LHA and Dec. indicator with dual scales with a movable flag covering one of the scales. When R cosine α goes to zero, the flag on the LHA scale changes position. When R sine α goes to zero the flag on the Dec. scale changes position, thereby providing four quadrant coverage.[4-5]

Now that the vector has been rotated and its correct quadrant established, the new X and Y must be found, and in turn, the new A and B. R cosine α now becomes the known value with X the unknown. The relay that disconnected the error signal from the sine-cosine potentiometer motor, connects this signal with the X servomultiplier drive. This X drive now positions the X potentiometer so that X is once more equal to R cosine α. By changing X the original equation is unbalanced so that an error signal is obtained from the equation summing amplifier. The versatile little relay once again comes to the rescue. When the relay was activated, it

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[4]It was felt that the added lines and relays for this operation would cause more confusion than they would do good, so this portion of the network is not included on any of the schematic diagrams.

[5]An alternate design for taking quadrant change into consideration was tried but found difficult to construct. A full discussion of this design is included as Appendix C.

disconnected the equation error from the X drive and connected it to a motor that controls the A input. The A input is changed until the equation is once more balanced, and the equation error output is zero. Meanwhile, the Y section of the computer has been undergoing the same type of changes as those outlined for X, except that Y is matched with R sine α, and the B input is adjusted to balance the equation. The problem is now completely solved. The reading now on the Dec. scale is the H_c of the star, and the reading on the LHA scale is the Z.

To aid the reader to better understand the many steps above, a block diagram of the entire computer is included as Figure 7, and a complete schematic of the computer is included as Figure 8.

In order to test the validity of the above design, a model of the computer was constructed. As construction of the model progressed, changes were made in the design to accommodate unforseen difficulties. The design presented above incorporates all of these changes. In some cases, availability of parts restricted refinement of the model, but it was not intended that the constructed model should physically resemble the finished product. The model was constructed only to prove or disprove the feasibility of the proposed design. Chapter IV outlines the experimental results obtained from the model and compares them to those obtained from the T-1 computer. The number of operational amplifiers required by the design presented in this study, exceeded the supply of Philbrick plug in type amplifiers on hand, making it necessary to use some

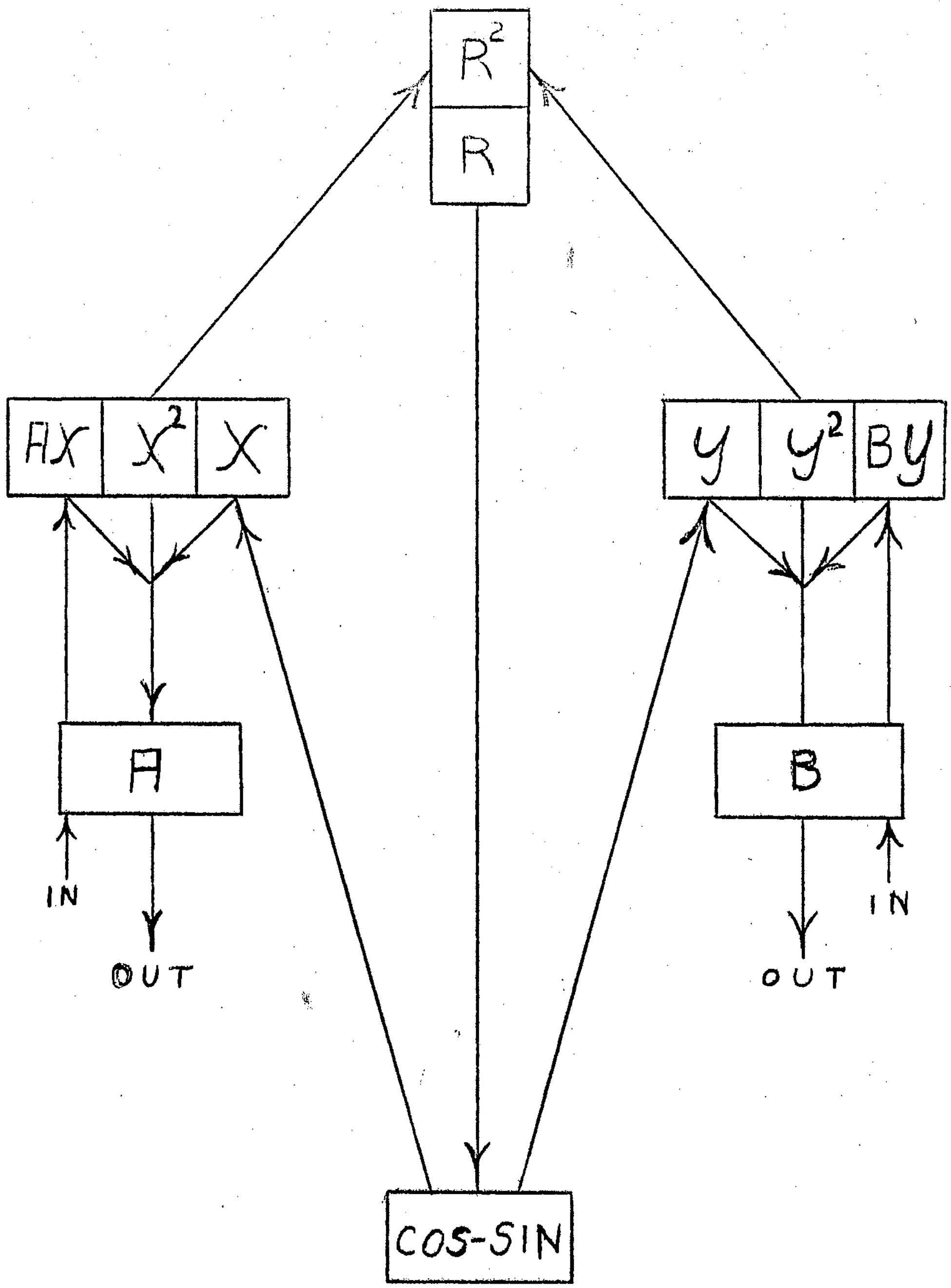


Figure 7. Computer Block Diagram

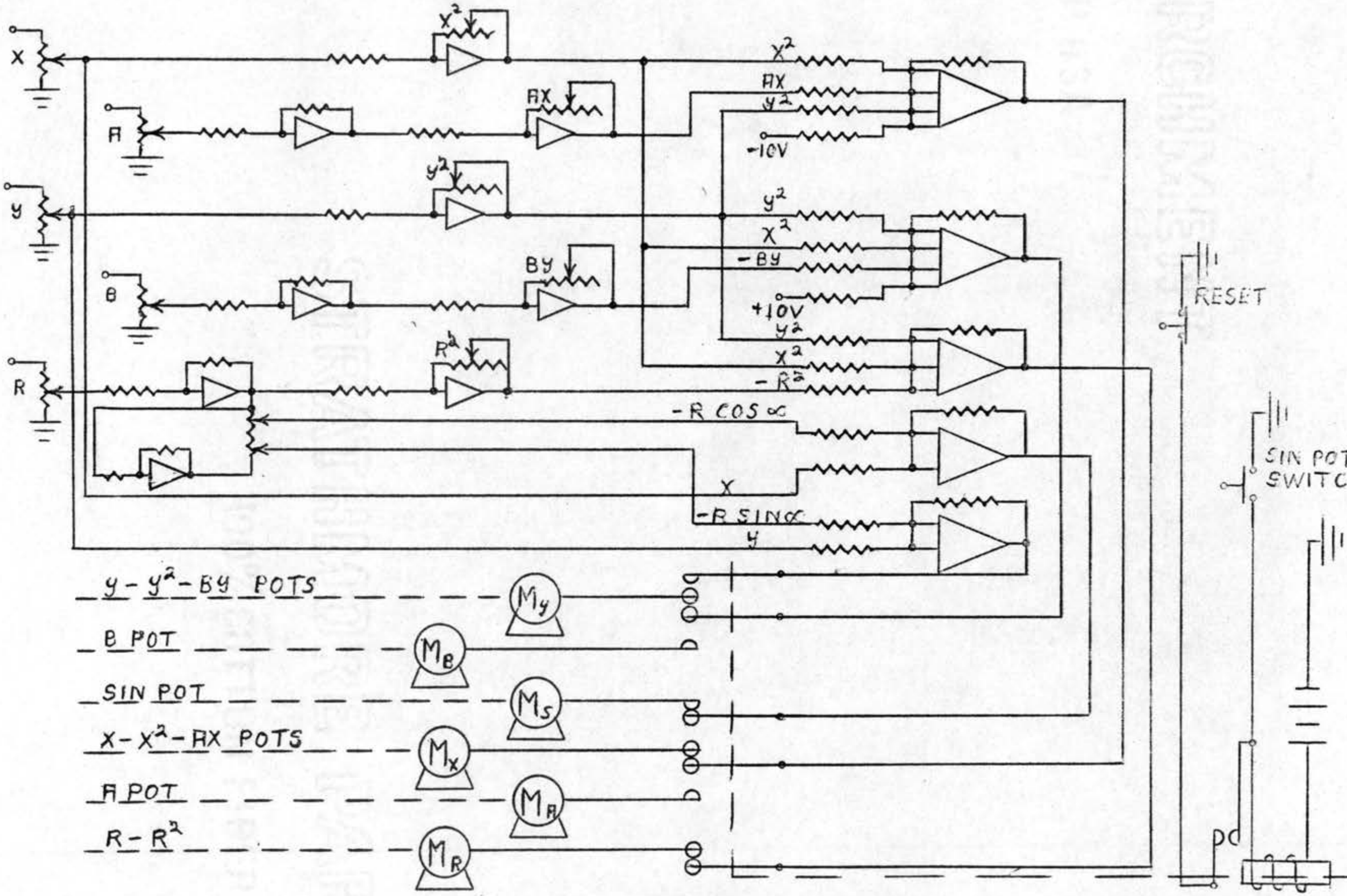
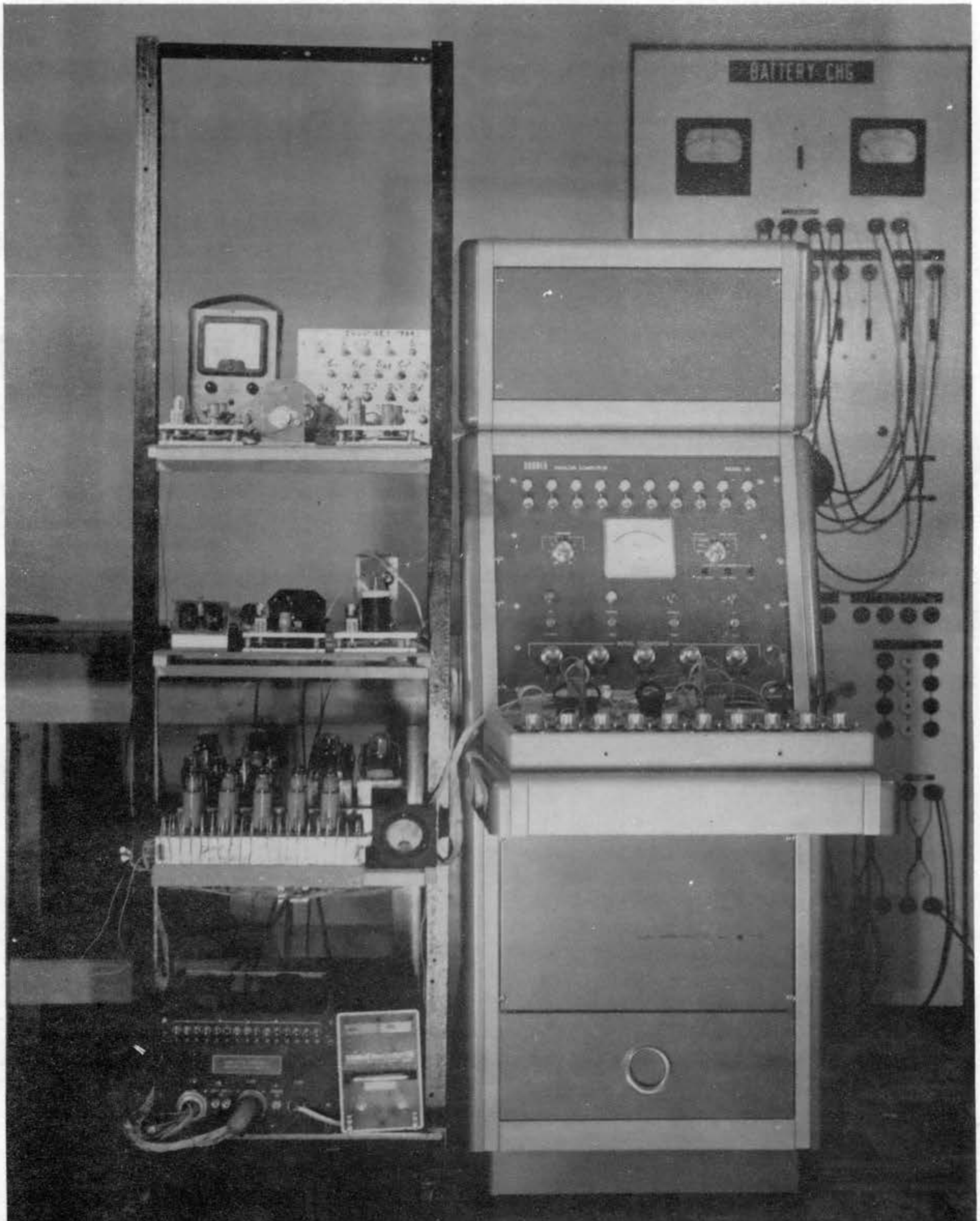


Figure 8. Computer Schematic

of the amplifiers available on the Donner Analog Computer. A photograph of the complete model as it was used during tests is shown in Plate IV.

Although the model as pictured in Plate IV is large in size, miniaturization techniques and proper selection of components would result in a much smaller and compact instrument. The amplifiers would all be transistorized. Power supplies already available on the aircraft would be used, and proper mounting and gearing of motors and potentiometer would be a must. The final manufactured item is visualized as being approximately the size of a cigar box and weighing between five and ten pounds. A refinement which would be of value would be a specific star input. The navigator normally uses only twenty-two of the major stars. The names of these stars would be printed on a setting dial with Dec. and SHA inputs available for whichever star was selected. It would then only be necessary to set in the GHA of Aries obtained from the Air Almanac, the assumed longitude, and the assumed latitude. This system would eliminate pencil computation of the LHA and reduce the navigators chance for error. A further refinement could be made so that a siderial clock mechanism would drive the GHA input. The navigator would set the GHA of Aries at the first of the flight and from that time would only need to set in the star he was using and his assumed latitude and longitude. A disadvantage of the siderial drive would be that precomputation would be limited without the use of a

PLATE IV



The Model

correction factor. With the star input incorporated, the navigator would be limited to the use of the twenty-two navigation stars and could not use the sun, moon, or any of the planets. Either or both of these refinements could be incorporated as an additional section of the computer at the cost of added size and weight.

One of the main advantages of this computer is its simplicity of use. To operate the computer with its refinements installed, the navigator would:

1. Push the reset button.
2. Set in the selected star.
3. Set in the assumed longitude.
4. Set in the assumed latitude.
5. The H_e and Z would be read from counter type indicators.

CHAPTER IV

EXPERIMENT RESULTS

After the model was completed, general operation throughout its entire range was accomplished. After minor adjustments were made, performance proved to be satisfactory. Experimentation was limited to setting in various LHA, Dec. and latitude inputs, and comparing the solutions to those obtained from the T-1. No Ageton or H.O. publication solutions were accomplished. Interpretation of the results was hamperred somewhat by the fact that the model output was on a straight numerical scale which had to be translated to degrees and minutes. It can be seen from the quantitative results, which are included as Appendix D, that some solutions are very close to the T-1, while some are not as close. The general trend of solutions, as shown on the graphs included in Appendix D, are sufficiently close to the T-1 solutions to be considered within experimental limitation. It must be kept in mind that the model was hand-built from available parts. Gears had excessive drag. Potentiometers were not matched, and in some cases were of too low a resistance for best results. Standard resistors were used, and, although trim pots were used, could not be matched perfectly. It is strongly felt that the experimental results indicate that there is no major flaw in the design.

Results of experimentation with the model indicate several critical areas which should be taken into account in further construction or design refinement. First and foremost, the computer will be only as accurate as the parts used in its construction. Stable operational amplifiers and power supplies must be used. It is suggested that trim pots be used to match resistors. Gearing ratios should be selected to increase accuracy to its limit, but care must be taken to eliminate gear drag and backlash to a minimum. Input voltages should be accurately controlled. Special attention should be paid to the sine-cosine potentiometer to insure that rotational accuracy is sufficiently high. It was found that operation near the X and Y axes was difficult. Further study of this area should be made in order to improve operation as X or Y approach zero.

If design for manufacture is undertaken, several recommendations for design changes are made. Potentiometers should be of as high a resistance as possible in order to minimize loading effects. Input voltages and power supplies should be selected so as to minimize drift and other small variations of DC inputs. Although it is essential that the isolation amplifier input and feedback resistors be matched, it is also desirable that they be of a high resistance so that the isolating properties of the amplifier will be the best possible. The possibility of using reversible DC motors should be investigated. In order to get the highest torque possible from the servo motors when the error signal is small, a design should be incorporated which would keep the driving voltage at a high level as long as an error voltage is present with a sharp drop to zero voltage when the error voltage reaches zero. As a suggestion, it may be found that cathode-follower type voltage dividers will prove more satisfactory than those used in the present design.

CHAPTER V

FUTURE DEVELOPMENT

The computer design presented in this study presents several opportunities for further development and future use. The basic computer as presented here is intended for use by the individual aerial navigator. It is not known whether the high degree of accuracy required in sea navigation would limit its use for the sea navigator or not, but this is surely an area that should be investigated. In short, wherever men use the stars as their guide, this computer should be a valuable aid if not their prime instrument.

Other possibilities for future use present themselves. Air-borne star followers exist which unerringly follow a star through the heavens. From the star follower an up-to-date H_o is received at all times. It would then be logical to construct a computer that would continuously present desired position information for a precomputed track. A continuous H_c could be attained by using this desired position as the assumed position input for the electrical analog of the T-1. By comparing the H_c from two of the electrical T-1's to the H_o of two star followers, a vectorial position error could be obtained. This error signal could then be made to control an automatic pilot system in such a manner as to correct this error. When this is done, a completely automatic guidance system is obtained.

The author is not familiar with the special problems of interplanetary navigation, but it seems quite plausable that the principles used in the design of this computer would be adaptable to space travel. Different basic equations would probably be necessary. Possibly a third equation with a third unknown would also be necessary. The basic function of the computer is the solution of simultaneous algebraic equations, so it does not matter if the equations are the same or whether a third equation is added.

The last statement suggests that the methods used for this computer could also be used for any problem that involves simultaneous algebraic equations. It may also be noted that the vector forming and vector rotation sections of the computer may have a wide field of application outside of the specific navigation problem discussed in this study.

CHAPTER VI

SUMMARY AND CONCLUSIONS

As the history of navigation is traced through the ages it can be seen that there is a never ending demand for more modern equipment. Equipment which works more quickly and efficiently. One of the primary needs of the present day navigator, is some device to lighten the work load and reduce the margin of error when celestial computations are made. One such device is the T-1 celestial computer which relies on a rotatable etched glass plate and optical reading device for presentation of the desired information. The T-1 has proved to be impractical for use in the air due to inherent mechanical and optical limitations. In this study an attempt was made to eliminate these limitations by putting the basic principles of the T-1 into mathematical form, then solving the resultant equations by electrical analog methods.

The computer design used the principle of the servo-multiplier which combines the position of a motor driven potentiometer arm with an input voltage to result in a variable multiplication. Algebraic addition of the signals from several of these servo-multipliers is then accomplished through use of operational type high gain D.C. summing amplifiers. This algebraic addition results in an error signal, which in turn, causes the servo-multipliers to be repositioned until the error signal is zero. By using this system of multipliers and adders, the mathematics associated with the T-1 are solved, and final results are presented on counter type indicators.

In order to test the validity of the basic design presented in this study, a working model was constructed. A number of sample problems were worked on this model and experimental data tabulated. This experimental data indicated that the basic design was sound, but that further refinement is needed to obtain the four or five place accuracy needed for celestial navigation. In future study toward this refinement, particular attention should be paid to reduction of mechanical drag, accuracy of components, and stability of amplifiers. In order to obtain the desired accuracy it may be necessary to include some digital type storage units for presentation of the higher order numbers with the analog section responsible only for the lower two or three orders. As an example, if it were desired to present 148° 53', the 53' could be reproduced effectively by the analog component while the 148° could be made to change in discreet 1° steps every time the lower register passed through 60'.

Looking toward future design, several suggestions have been presented. It is felt that for certain specialized cases it may be desirable to include a siderial clock drive and specific star input. The following is quoted from the magazine, <u>Aviation</u> <u>Week</u>, published 6 April 1959, under the heading "Future Guidance Systems";

> Inertial systems in combination with automatic star trackers, appear likely to play the dominant role in interplanetary space navigation. Here, however, the inertial system's primary role will be to provide spatial stabilization for the star trackers to keep them approximately aligned on the star.

The computer design presented in this study is highly adaptable to combination with the star tracker. The information obtained from the star tracker must be combined with information about the desired track which is the information available from this design. It appears likely that there will be a growing demand for a device such as the one presented in this study.

Conclusions to be drawn from study of the basic design and model of this computer are that:

1. The basic design is sound.
2. Further study and refinement are needed to increase accuracy.
3. The methods used have a wide range of application in problems involving solution of simultaneous algebraic equations, vector forming, or vector rotating.

SELECTED BIBLIOGRAPHY

Ageton, Arthur Ainsley. Manual of Celestial Navigation. New York: D. Van Nostrand Company, 1942.

Johnson, Clarence L. Analog Computor Techniques. New York: McGraw-Hill Book Company, 1956.

Keistor, William, Alistair E. Ritchie, and Seth H. Washburn. The Design of Switching Circuits. Princeton: D. Van Norstrand Company, 1957.

Nautical Almanac Office, United States Naval Observatory, The Air Almanac. Washington: United States Government Printing Office, Current.

Reich, Herbert J. Theory and Application of Electron Tubes. New York: McGraw-Hill Book Company, 1944.

Thaler, George J, and Robert G. Brown. Servomechanism Analysis. New York: McGraw-Hill Book Company, 1953.

United States Hydrographic Office. Useful Tables From The American Practical Navigator, H.O.No. 9 Part II. Washington: United States Government Printing Office, 1940.

United States Hydrographic Office. H.O. 218. Washington: United States Government Printing Office.

United States Hydrographic Office. H.O. 249. Washington: United States Government Printing Office.

Weems, Philip Van Horn. Simplified Celestial Navigation. Annapolis: Weems System of Navigation, 1940.

APPENDIX A

PREVIOUS WORK

During a tour of duty as a project engineer in the Equipment Laboratory at Wright-Patterson Air Force Base, Dayton, Ohio, the author worked on the problem of making the T-1 computer more practical. At that time an attempt was made to solve the problem by mechanical means. The following is a direct abstract of this work which was accomplished in February, 1948. The problem was never completely solved due to the transfer of the author to other duties. No attempt at further investigation along mechanical lines has been made in this study. The information below is included as another possible approach to the solution of the problem.

MECHANICAL T-1 COMPUTER

This is a mechanical celestial computing device. By turning three control cranks, the computed Altitude and Azimuth for any star or planet can be read for any assumed position.

Operation for this device is as follows:

1. Turn LHA crank until correct LHA is read on LHA counter.

2. Turn Dec. crank until correct Dec. is read on Dec. counter.

3. Press engage button.

4. Turn latitude crank until correct latitude is read on latitude counter.

5. Read H_c on Dec. counter.

6. Read Azimuth on LHA counter.

This devise is essentially the same as the T-1 computer except that no visual aligning is necessary. The problem encountered is to make a pointer travel over a flat plate to a certain point located on a curved line. To accomplish this, three integrating devices are used. These integrating devices are of the ball, disk, roller type. Positioning of the pointer (equivalent to the eyepiece on the T-1) is accomplished as follows:

When the LHA crank is turned it positions the ball on the base of three disks. (Two of these disks are in reality a single plate with two surfaces and a ball roller on each side.) These three ball roller devices will be named as follows:

1. LHA drive.

2. Dec. integrator.

3. Dec. drive.

Turning the LHA crank will not only position the three balls but will also drive the pointer across the equatorial axis of the master plate a distance proportional to the LHA and will turn the LHA counter.

Turning of the Dec. crank will cause rotation of the disks.

Motion of the Dec. integrator will be transmitted to the ball of the Dec. drive causing it to move toward or away from the center of its disk. The ball of the Dec. drive is made to roll by its disk and transmits this motion through its roller to the Dec. counter and the pointer. Turning of the Dec. crank causes the disk of the LHA drive to rotate. The movement is transmitted through the roller of the LHA drive to the pointer but does not change the LHA counter reading.

Upon completion of setting LHA and Dec., the engaging button is pushed. This fastened the pointer to the master plate by means of electromagnetism or some other method that might be thought of later. The engaging button also disconnects the LHA and Dec. cranks. The master plate is the same as the master plate of the present T-1 computer except that it is made of metal and has no numerals.

Next, the latitude crank is turned which causes the master plate to rotate in the opposite direction but in the same amount as the master plate of the T-1. This turning of the master plate carries the pointer along with it causing the LHA and Dec. indicators to change. Final reading is H_c and Azimuth.

Investigation should be made as to the feasibility of using a ball as the pointer. This ball would have two roller pick-offs, one for LHA change and the other for Dec. change. This would be used instead of the electromagnet mentioned above.

In order to get the correct movement it may be necessary to have the rollers, cone shaped.

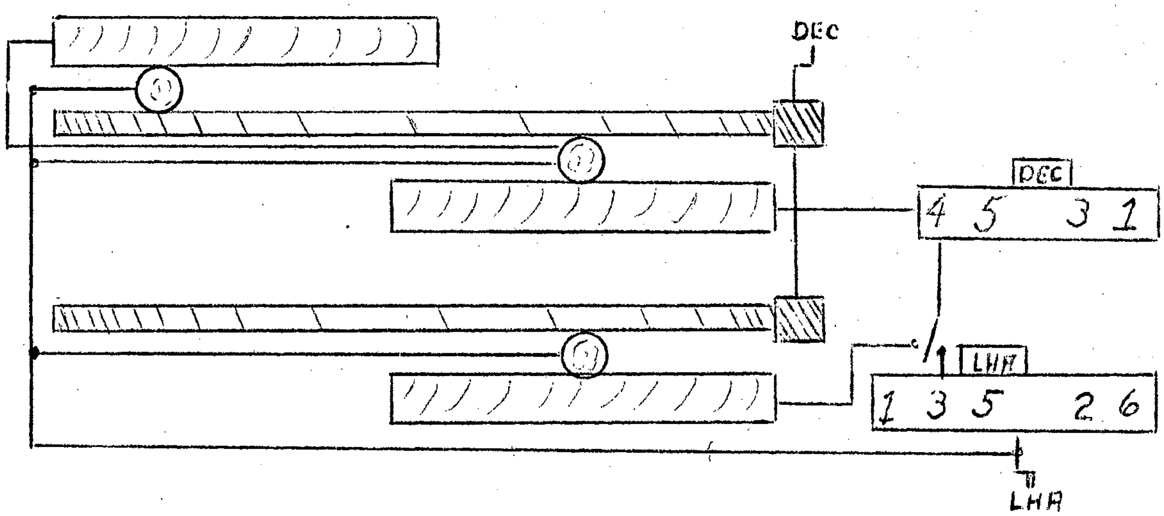


Figure 9. Mechanical T-1

APPENDIX B

DEVELOPMENT OF EQUATIONS

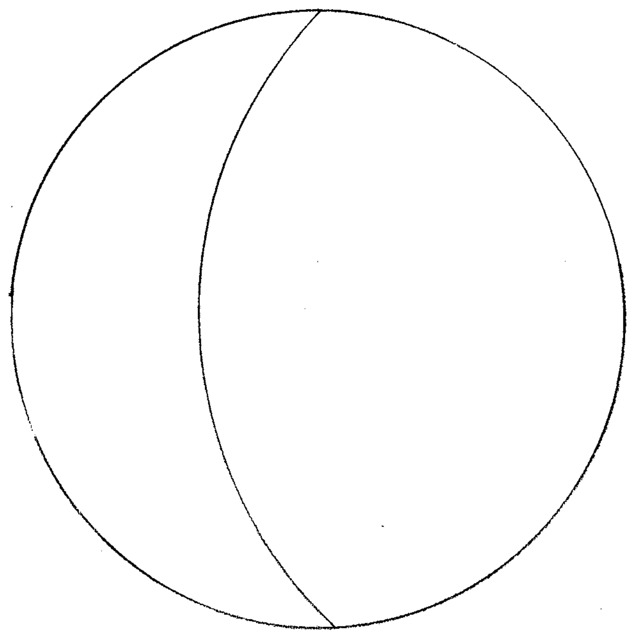


Figure 10. Vertical Curved Lines

To write the equation of a circle through the three points (0,a), and (0,-r) and (+a,0)
$(x-h)^2 + (y-k)^2 = R^2$ where R is the radius and (h,k) is the center of the circle.

$$h^2+(r-k)^2 = R^2 = h^2 + r^2-2rk + k^2$$

$$h^2 + (-r-k)^2 = R^2 = h^2 + r^2 + 2rk + k^2$$

$$(a-h)^2 + k^2 = R^2 = a^2-2ah + h^2 + k^2$$

$$4rk = 0$$

$$k = 0$$

$$h^2+r^2 = R^2$$

$$a^2 \quad -2ah + h^2 = R^2$$

$$a^2 \quad -2ah + h^2 = h^2+r^2$$

$$a^2-2ah-r^2 = 0$$

$$2ah = a^2-r^2$$

$$h = \frac{a^2 - r^2}{2a}$$

$$\frac{(a^2-r^2)}{2a}^2 + r^2 = R^2$$

$$\frac{a^4-2a^2r^2+r^4}{4a^2} + r^2 = R^2$$

$$4\,a^2\,R^2 = a^4 + 2a^2r^2+r^4$$

$$R^2 = \frac{(a^2+r^2)^2}{4a^2}$$

$$R = \frac{a^2+r^2}{2a}$$

$$\left(x-\frac{a^2-r^2}{2a}\right)^2 + y^2 = \left(\frac{a^2+r^2}{2a}\right)^2$$

$$x^2 - \frac{a^2-r^2}{a} \quad x + \frac{(a^2-r^2)^2}{4a^2} + y^2 = \frac{(a^2+r^2)^2}{4a^2}$$

$$4a^2x^2-4a(a^2-r^2)x + (a^2-r^2)^2 + 4a^2y^2 = (a^2+ r^2)^2$$

$$4a^2x^2 \; -4a(a^2-r^2)x + 4a^2y^2 = 4a^2r^2$$

$$x^2- \frac{a^2-r^2}{a} \, x + y^2-r^2 = 0$$

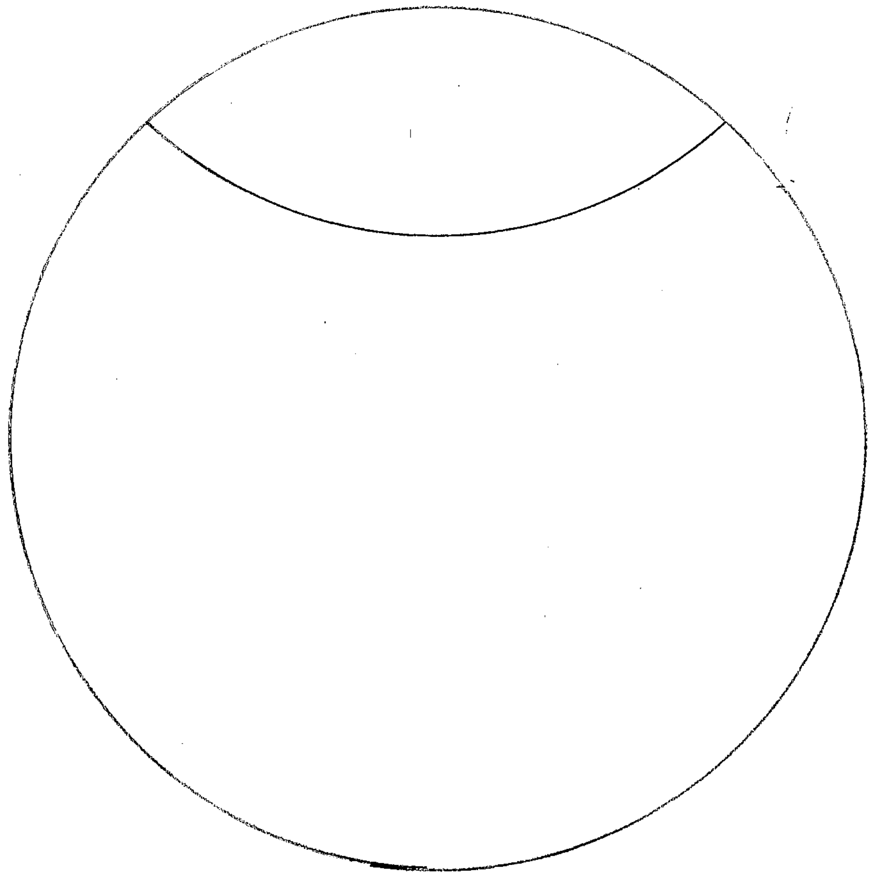


Figure 11. Horizontal Curved Line

$$x^2 + (y-r\ \sec\Theta)^2 = (r\ \tan\Theta)^2$$

$$x^2 + y^2 - 2yr\sec\theta + r^2\ \sec^2\theta\ - r^2\tan^2\theta = 0$$

$$b = r(\sec\theta\ - \tan\theta) = r\ (\sec\theta\ - \mathrm{Sec}^2\theta - 1)$$

$$(b-r\ \sec\theta)^2 = r^2\ (\sec^2\theta - 1) = b^2 - 2br\ \sec\theta + r^2\ \sec^2\theta$$

$$r\ \sec\theta = (b^2 + r^2)/2b$$

$$x^2 - \frac{b^2 + r^2}{b}\ y + y^2 + r^2 = 0$$

APPENDIX C

ALTERNATE DESIGN

The design presented in this Appendix, and shown in schematic form in Figure 12, was the design which was used throughout most of the construction of the model. A great deal of difficulty was encountered in attempting to impress a positive and negative voltage from the same source on the end terminals of a potentiometer. To prevent excessive loading problems, it was found necessary to use two isolation amplifiers for each potentiometer. This was in addition to the previously required amplifier. There were too few operational amplifiers available to continue with this design, so the design presented in the main body of this study was devised.

It is believed that the design presented in this Appendix has certain advantages, especially in quadrant selection, and warrants further study.

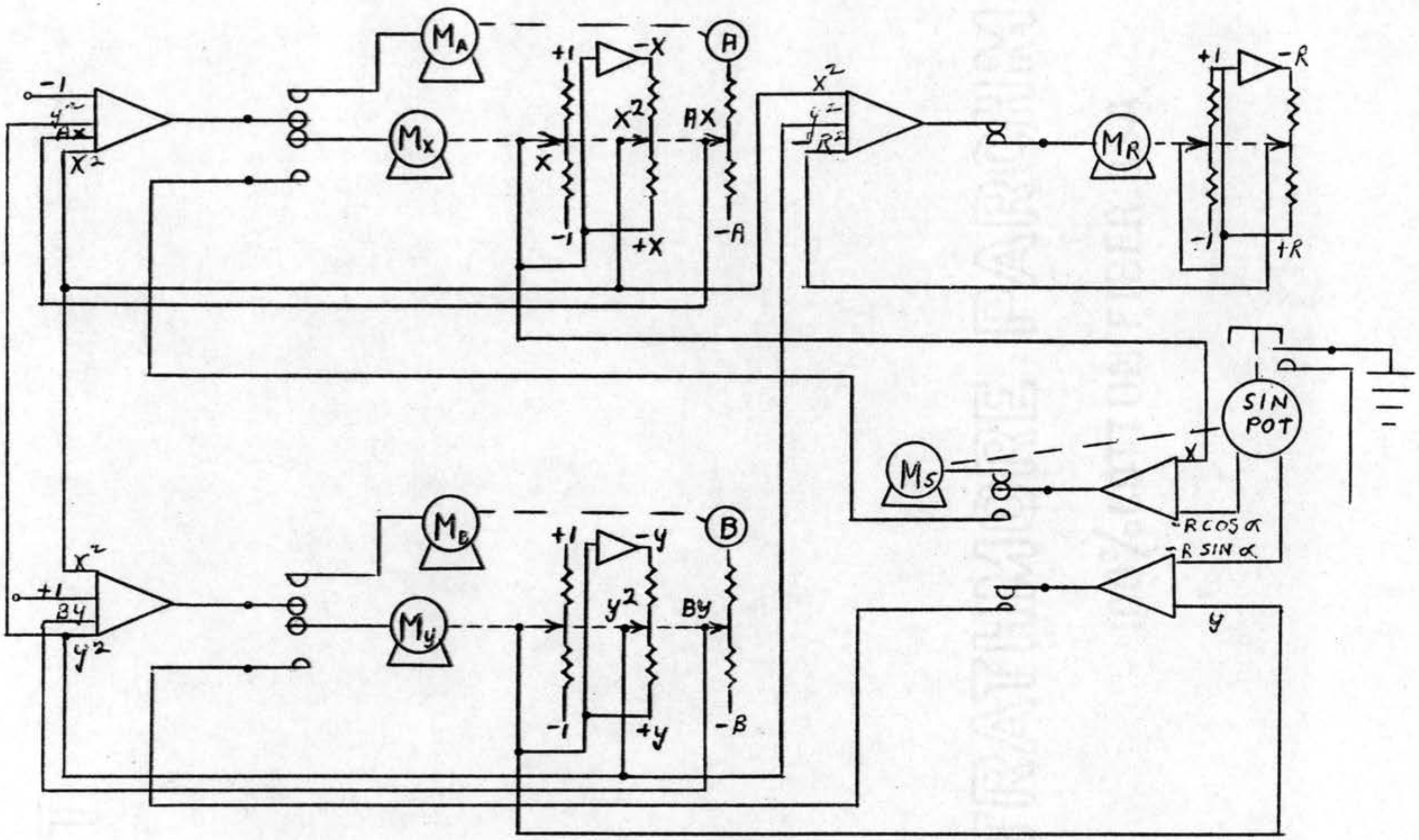


Figure 12. Alternate Design

APPENDIX D

EXPERIMENTAL RESULTS

After the model was completed, a number of sample problems were solved in order to check the operation and accuracy of the device. The numerical results of these test problems are presented in this appendix.

In order to obtain the best results, all voltages were checked as accurately as possible with the available Heathkit and Hickock voltmeters. All bias networks were checked and carefully set.[6] All resistors were carefully set, and all counters were calibrated.

After general operation of the model was checked, four major sets of information were obtained. Each set of information consisted of one input LHA and Dec. The assumed latitude was then varied, in ten degree steps, between 0 and 50 degrees. The following data was obtained from the computer. In this data the A of the Model is analogous to the LHA set on the vertical curved lines of the T-1. The B of the model is analogous to the Dec. set on the horizontal

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[6]It proved impossible to eliminate all drift in the bias of the Philbrick operational amplifiers. The bias network used for these amplifiers was substantially affected by slight changes in input or feedback resistance. Future model design should incorporate bias networks which are not affected by input and feedback resistance changes.

curved lines of the T-1. The Lat. is the assumed latitude and represents the number of degrees which the vector was rotated.

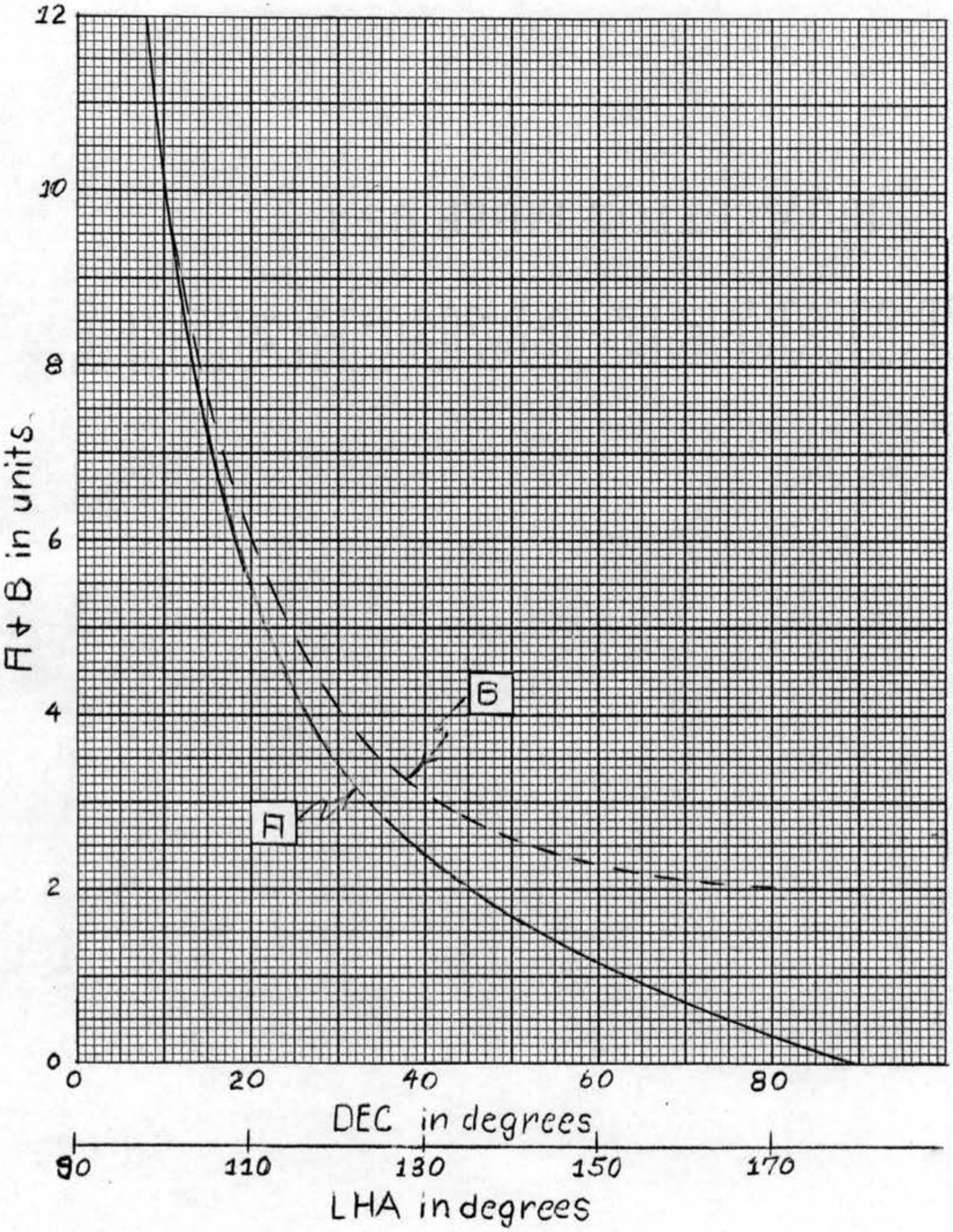
Lat.	0	10	20	30	40	50
A	154	162	165	166	169	170
B	57	52	42	37	20	10
A	134	140	143	145	149	149
B	34	31	26	18	10	x
A	122	125	125	132	134	132
B	30	26	23	15	x	x
A	117	120	123	125	125	125
B	27	23	17	10	x	x

In the above data, Lat. is in degrees north, A is in degrees LHA, and B is in degrees Dec. Due to the limitation of 10 volts to B, it was not possible to take Dec. readings of less than 10 degrees.

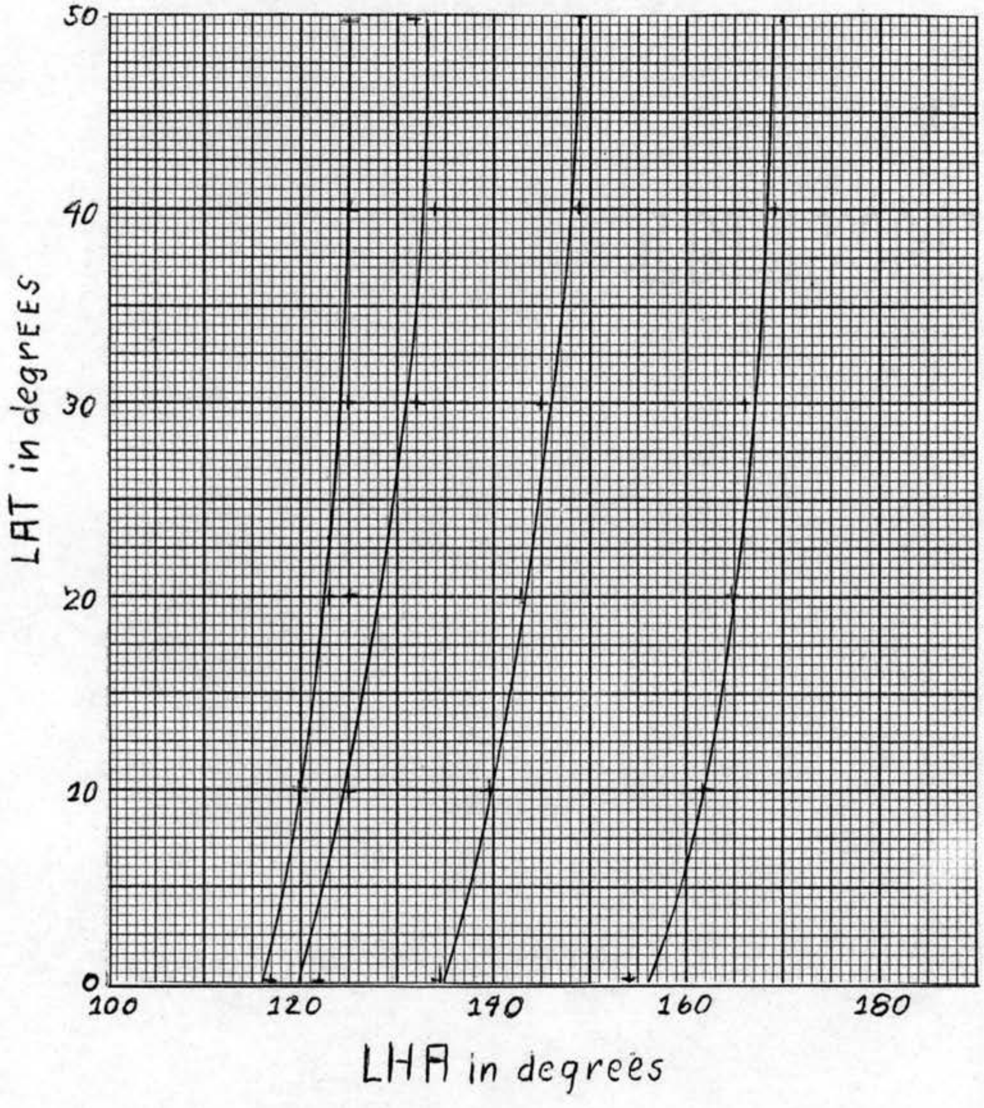
It was found that B did not vary linearly with changes of LHA, and A did not vary linearly with changes of Dec. This non-linear relationship was obtained by measurements from Plate III. The existing variation of A with changes of LHA, and variation of B with changes of Dec. are included as Curve Sheet 1.

In order to eliminate as much random error as possible, the rough data above was plotted on Curve Sheets 2 and 3. A smooth curve was drawn for each set of information.

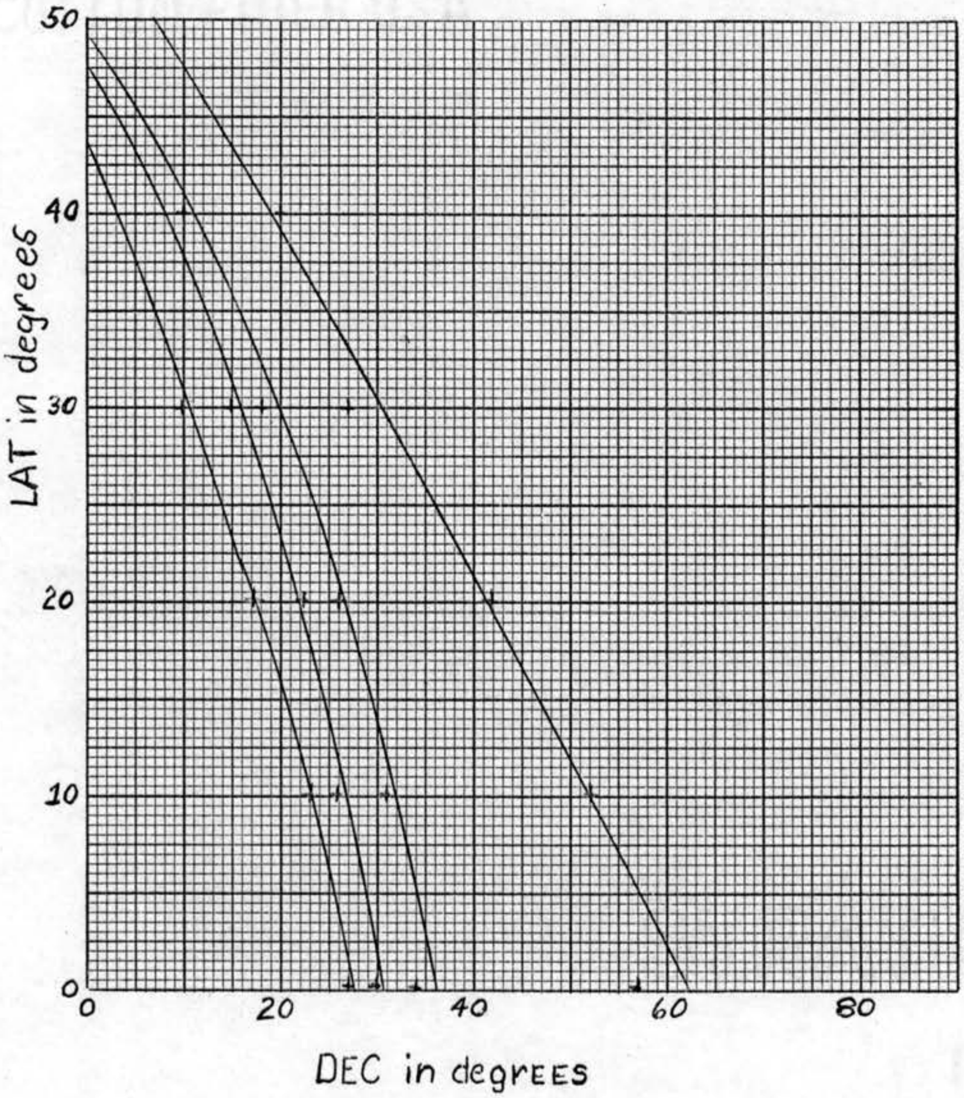
The same sets of information used for computation on the



Curve Sheet 1. A vs LHA Bvs DEC



Curve Sheet 2. A vs LAT Rough Data



Curve Sheet 3. B vs LAT Rough Data

model were then used for computation on the T-1.[7] The comparison between the data obtained from the T-1 and that obtained from the model is included in Tables I through IV.

Analysis of the Tables indicates that an accuracy of within approximately two degrees can be expected from the present model. Final design should have an accuracy of at least ± 1 minute, but with the components used in construction of this model the two degree error is considered to be well within experimental limits.

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[7]It was assumed that the T-1 was accurate, although it had not been used for several years.

TABLE I

COMPARISON OF T-1 AND MODEL DATA
INPUT LHA 156 DEC. 62

LAT	T-1		Model	
	LHA	DEC	LHA	DEC
10	161	52.6	162	51.0
20	165	42.0	165	41.0
30	167	30.0	167	30.0
40	168	20.0	168	19.5
50	169	12.0	169	07.0

TABLE II

COMPARISON OF T-1 AND MODEL DATA
INPUT LHA 135 DEC. 36

LAT	T-1		Model	
	LHA	DEC	LHA	DEC.
10	140	31.0	140	31.5
20	143	25.5	143	26.0
30	145	19.0	146	20.0
40	146	10.0	148	10.0
50	147	00.0	149	00.0

TABLE III

COMPARISON OF T-1 AND MODEL DATA
INPUT LHA 120 DEC. 31

LAT	T-1		Computer	
	LHA	DEC	LHA	DEC
10	125	25.6	124	26.5
20	127	21.0	128	21.5
30	130	15.0	131	15.5
40	131.5	08.0	133	08.0
50	132	01.5	133	00.0

TABLE IV

COMPARISON OF T-1 AND MODEL DATA
INPUT LHA 116 DEC. 27

LAT	T-1		Computer	
	LHA	DEC	LHA	DEC
10	120	22.0	120	23.0
20	123	17.0	122	17.0
30	125	11.0	124	10.0
40	126	05.0	125	03.0
50	126	-2	125	00.0

VITA

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Professional experience: Entered the United States Air Force in 1942, and now hold the rank of Major. Flew as a lead navigator in the European Theater of War during World War II. Instructed navigation for a short period then was assigned as a project engineer for celestial and dead reckoning navigation equipment at Wright Field Dayton, Ohio in 1945 and remained there, except for an eight month period out of the service, until 1948. Graduated from Pilot School in 1949 and instructed student pilots until 1953. Attended Oklahoma A & M College in 1953, spent a three year tour of duty as Electronic Synthetic Instrument Trainer Officer at Furstenfeldbruck, Germany, then returned to Oklahoma State University in January, 1957.