Oct. 27, 1964 D. W. BURBECK ETAL 3,154,780

AUTOMATIC SHORAN BOMBING SYSTEM

Filed June 16, 1959 8 Sheets-Sheet 1

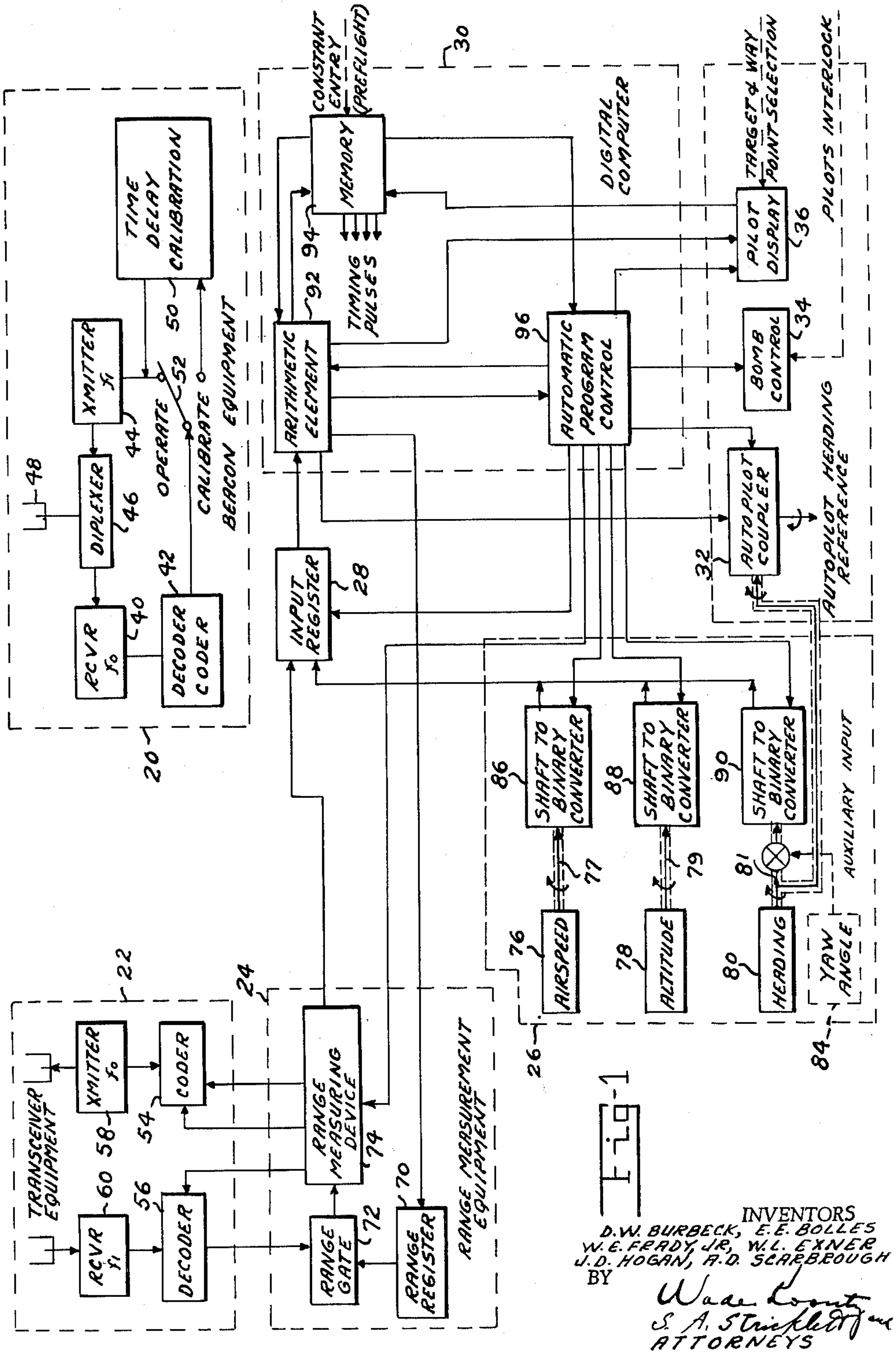


Fig-1

INVENTORS
D.W. BURBECK, E.E. BOLLES
W.E. FRADY, JR., W.L. EXNER
J.D. HOGAN, A.D. SCARBROUGH
BY
Wade Koontz
S. A. Stricklett
ATTORNEYS

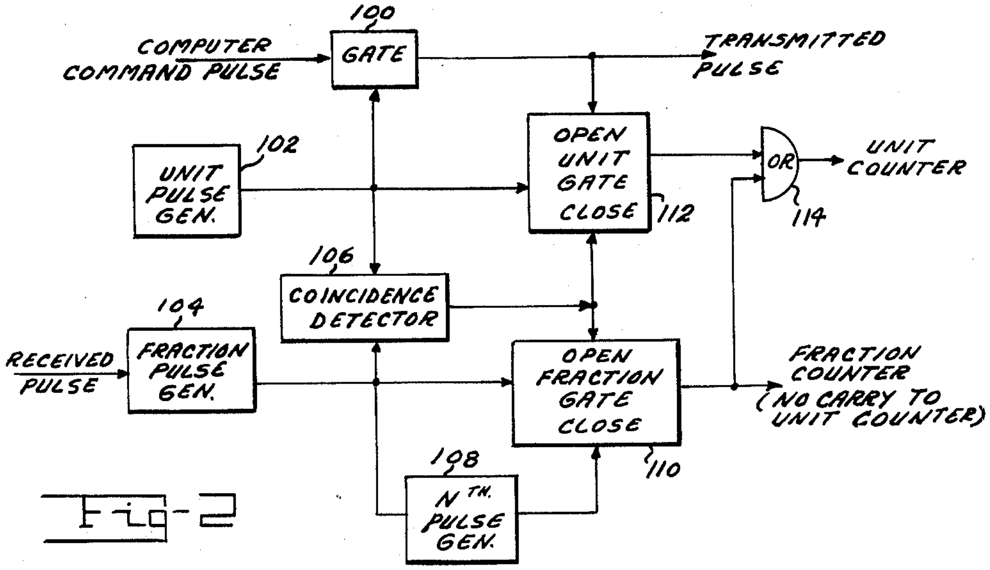


Fig-2

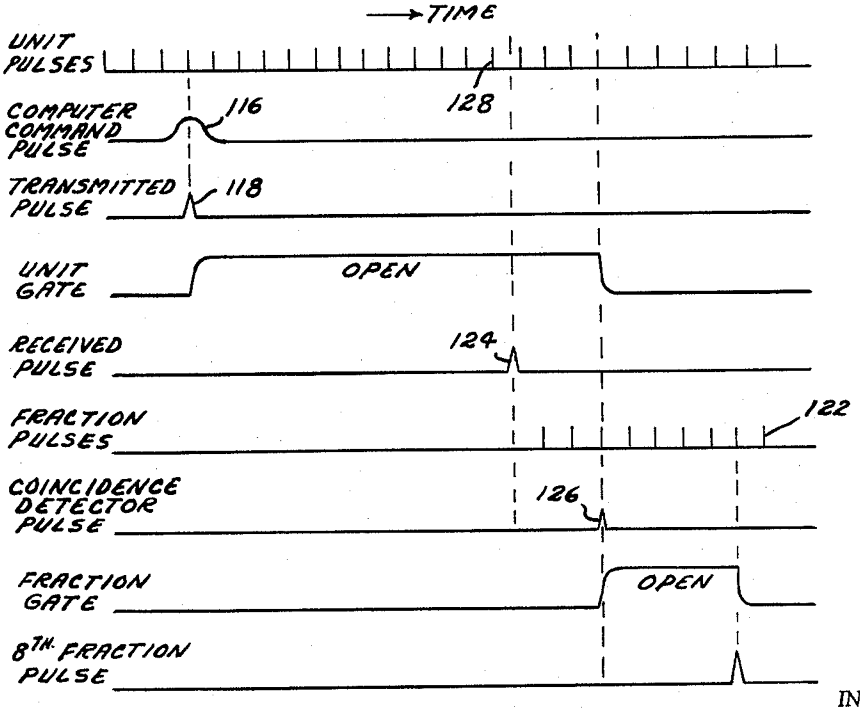


Fig-3

INVENTORS
D.W. BURBECK, E.E. BOLLES
W.E. FRADY, JR., W.L. EXNER
J.D. HOGAN, A.D. SCARBROUGH
BY
Wade Koontz
S. A. Strickler and
ATTORNEYS

Oct. 27, 1964 D. W. BURBECK ETAL 3,154,780

AUTOMATIC SHORAN BOMBING SYSTEM

Filed June 16, 1959 8 Sheets-Sheet 3

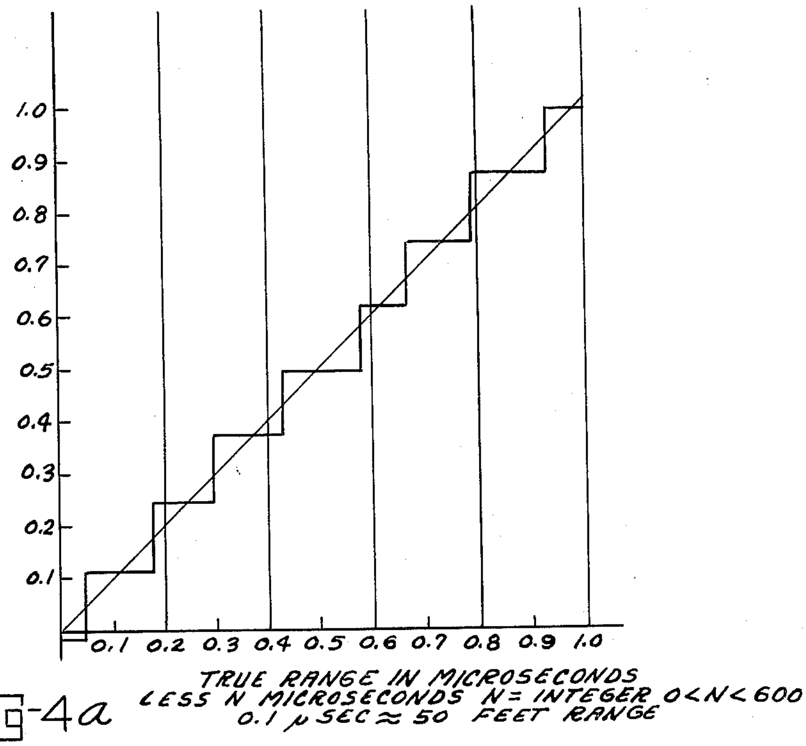


Fig-4a

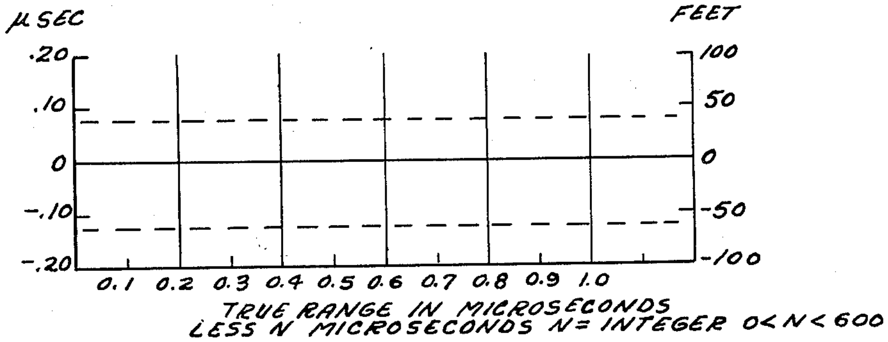


Fig-4b

INVENTORS
D.W. BURBECK, E.E. BOLLES
W.E. FRADY, JR., W.L. EXNER
J.D. HOGAN, A.D. SCARBROUGH
BY
Wade Koontz
S. A. Strickland
ATTORNEYS

Oct. 27, 1964 D. W. BURBECK ETAL 3,154,780

AUTOMATIC SHORAN BOMBING SYSTEM

Filed June 16, 1959 8 Sheets-Sheet 4

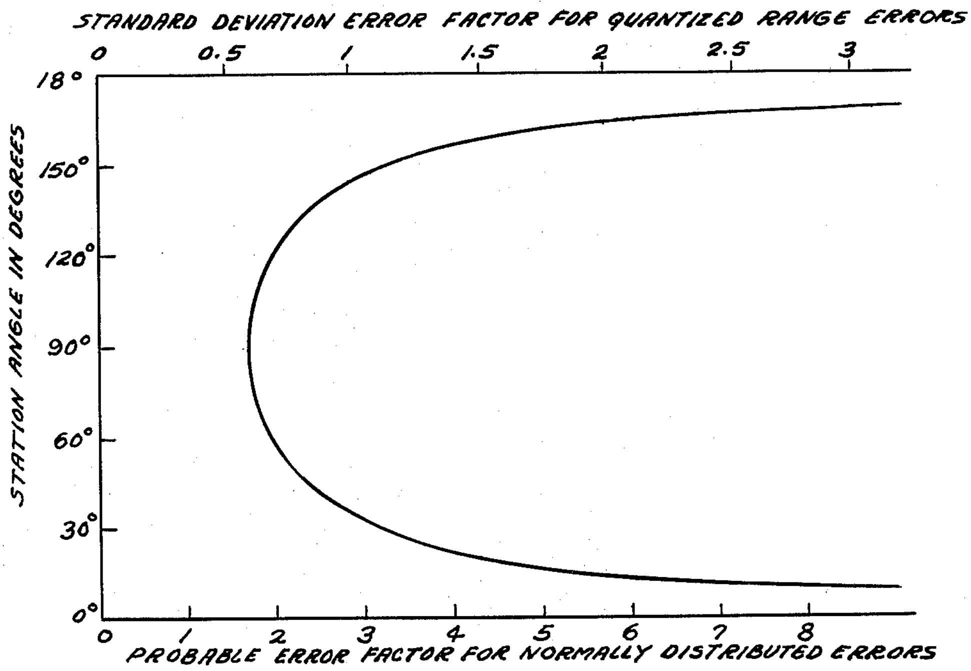


Fig-5

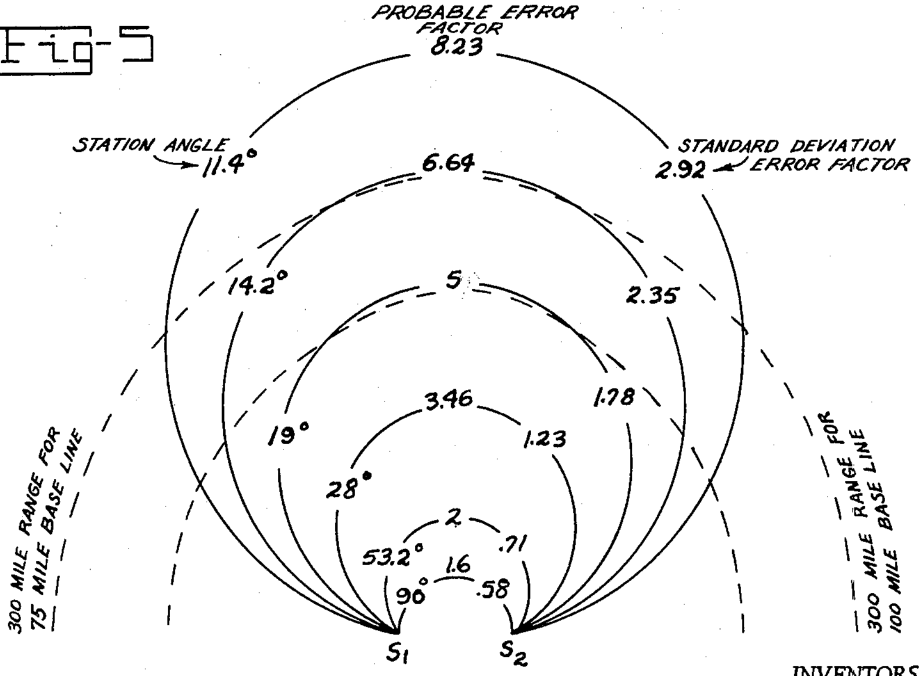


Fig-6

INVENTORS
D.W. BURBECK, E.E. BOLLES
W.E. FRADY, JR., W.L. EXNER
J.D. HOGAN, A.D. SCARBROUGH
BY
Wade Koontz
S. A. Strickler
ATTORNEYS

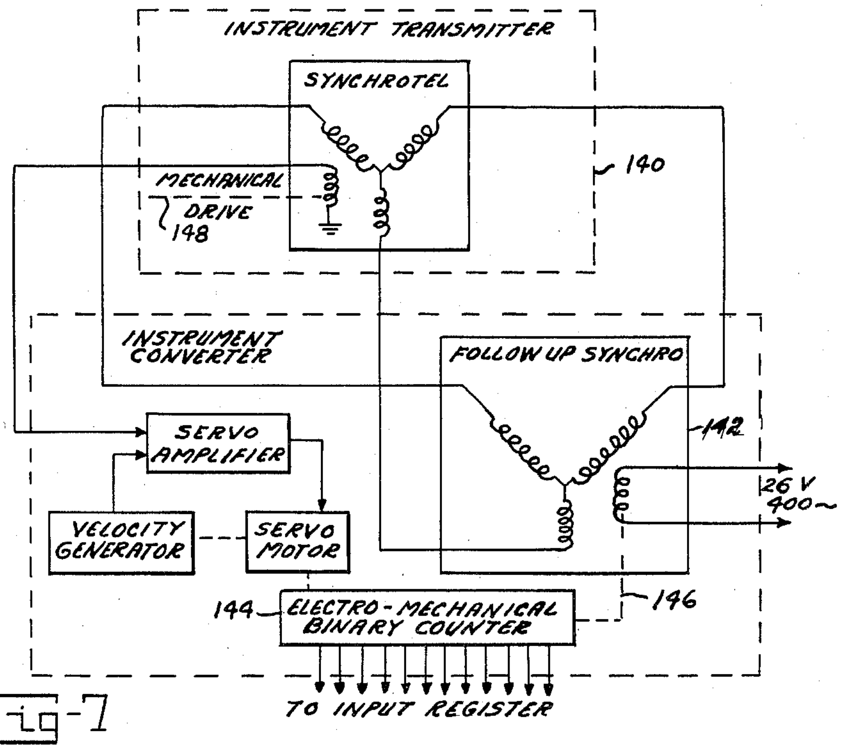


Fig-7

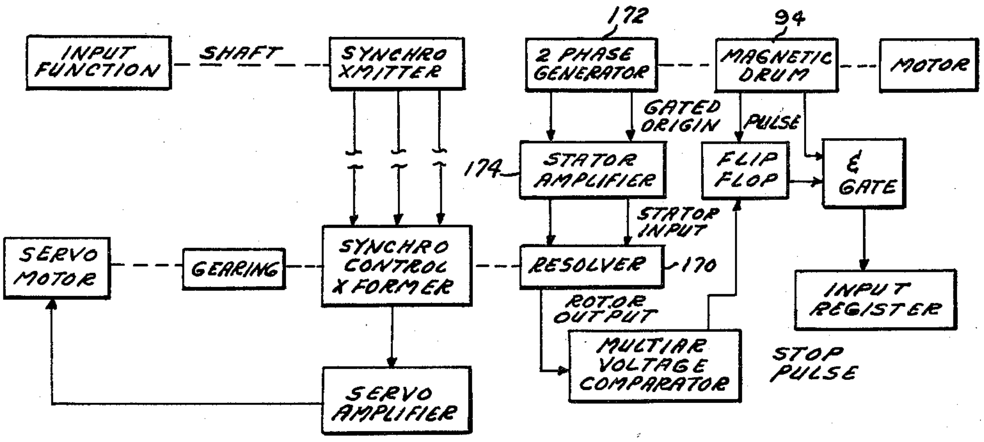


Fig-9

INVENTORS
D.W. BURBECK, E.E. BOLLES
W.E. FRADY, JR., W.L. EXNER
J.D. HOGAN, A.D. SCARBROUGH
BY
Wade Koontz
S. A. Stickle Jr
ATTORNEYS

Oct. 27, 1964 D. W. BURBECK ETAL 3,154,780

AUTOMATIC SHORAN BOMBING SYSTEM

Filed June 16, 1959 8 Sheets-Sheet 6

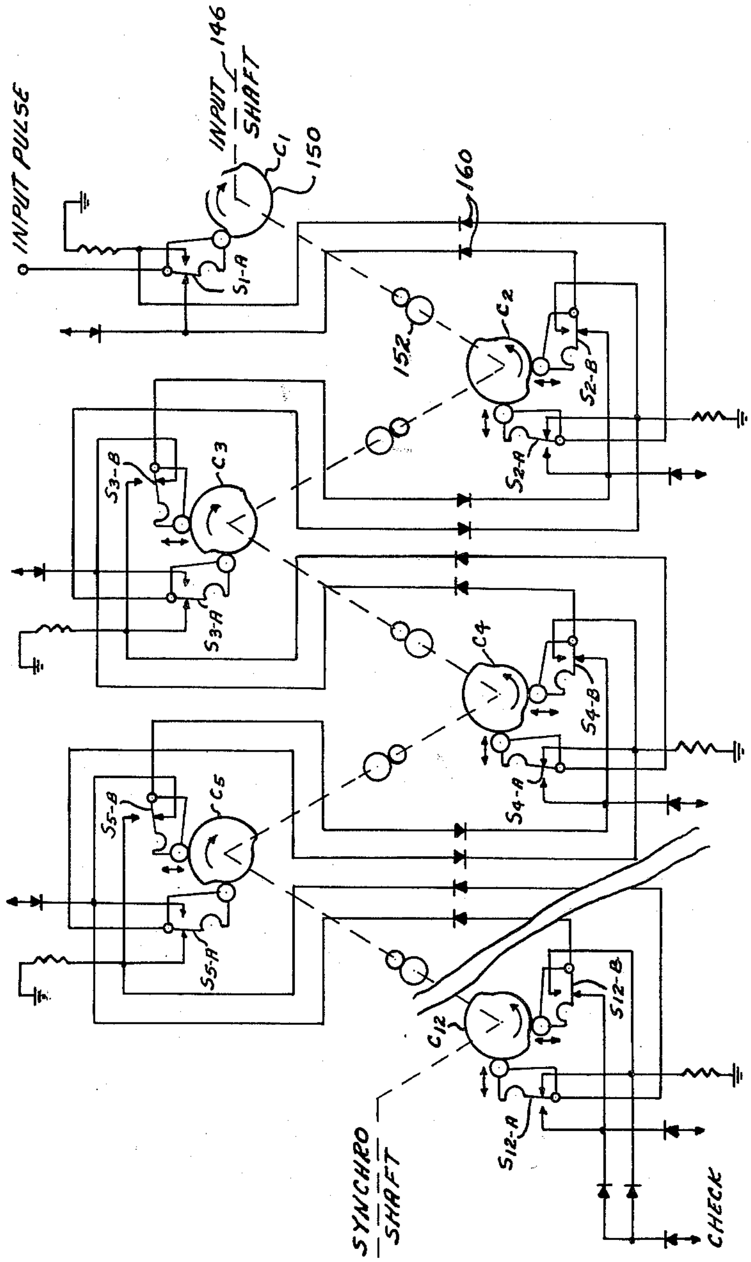


FIG. 8

INVENTORS
D. W. BURBECK, E. E. BOLLES
W. E. FRADY, JR., W. L. EXNER
J. D. HOGAN, A. D. SCARBROUGH
BY
Wade Koontz
S. A. Stickle Jr.
ATTORNEYS

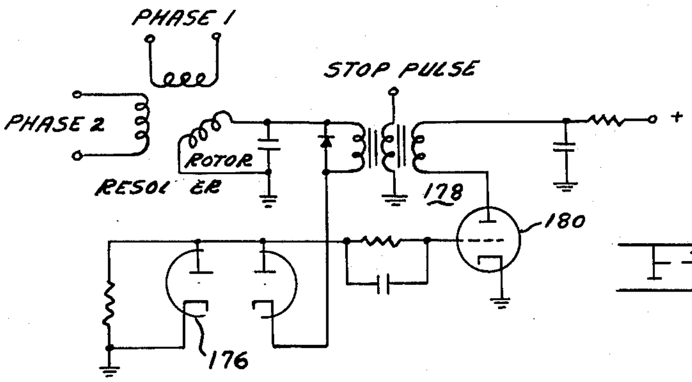


Fig-10

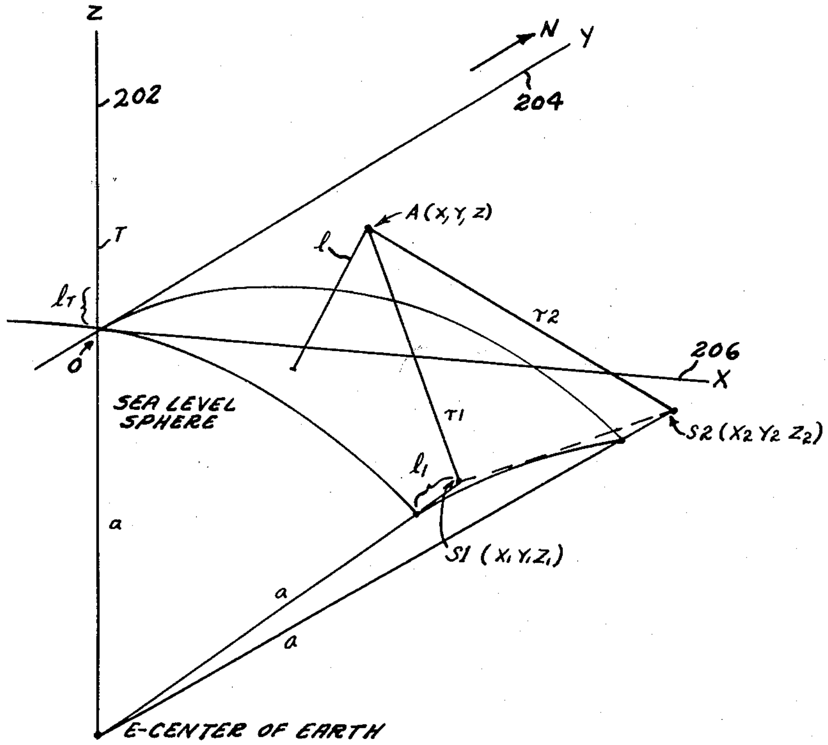


Fig-11

INVENTORS
D. W. BURBECK, E. E. BOLLES
W. E. FRADY, JR., W. L. EXNER
J. D. HOGAN, A. D. SCARBROUGH
BY
Wade Koontz
S. A. Strickler
ATTORNEYS

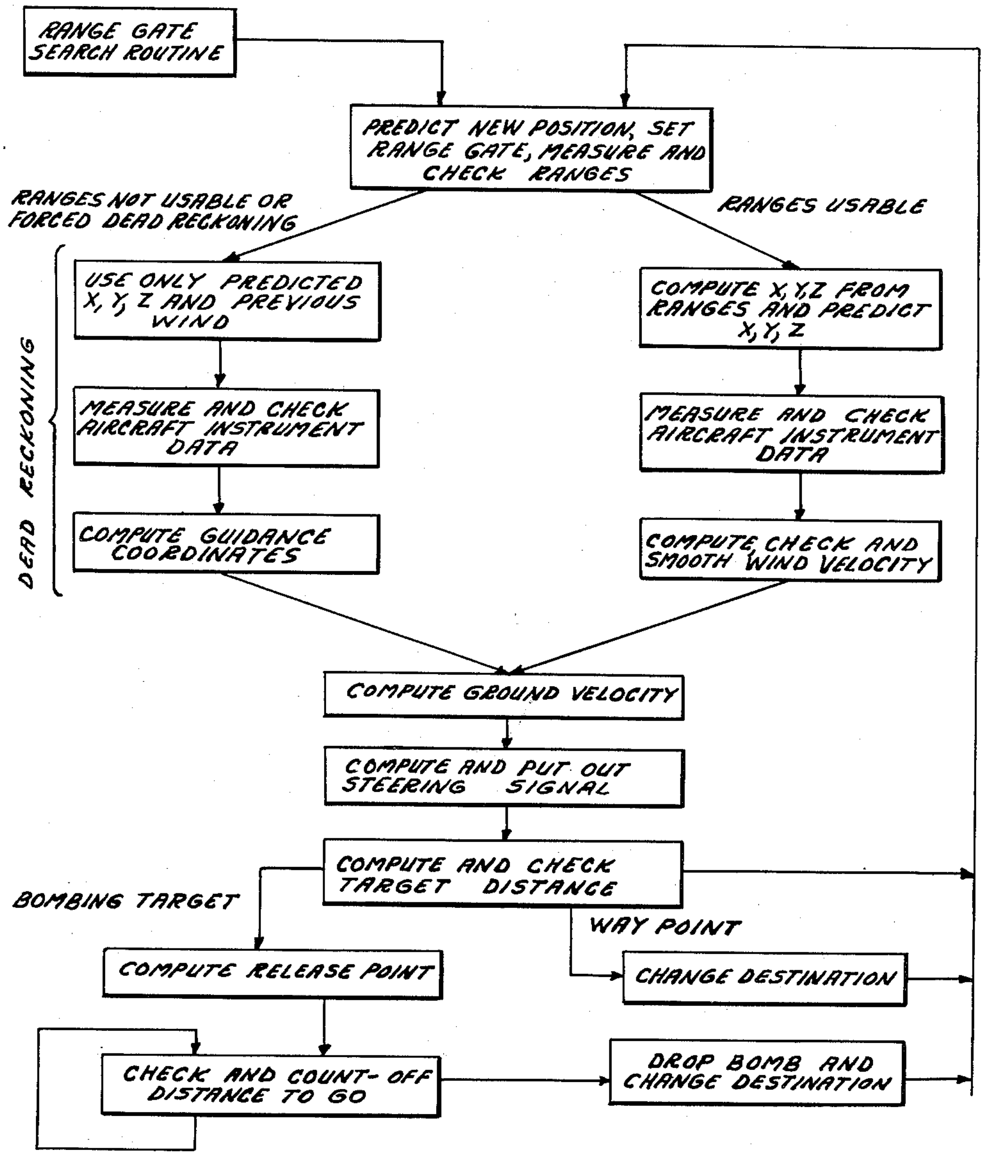


Fig-12

INVENTORS
D.W. BURBECK, E.E. BOLLES
W.E. FRADY, JR., W.L. EXNER
J.D. HOGAN, A.D. SCARBROUGH
BY
Wade Koontz
S. A. Stickler
ATTORNEYS

United States Patent Office

3,154,780

Patented Oct. 27, 1964

3,154,780

AUTOMATIC SHORAN BOMBING SYSTEM

Donald W. Burbeck and Elwood E. Bolles, Los Angeles, William E. Frady, Jr., Santa Ana, William L. Exner, Santa Monica, James D. Hogan, Rolling Hills Estates, and Alfred D. Scarbrough, Palos Verdes Estates, Calif., assignors to the United States of America as represented by the Secretary of the Air Force

Filed June 16, 1959, Ser. No. 820,838

1 Claim. (Cl. 343—13)

This invention relates to an automatic shoran bombing system and particularly to a navigation and bombing system utilizing an automatic digital computer for controlling the navigation of the vehicle and the bomb release.

Heretofore a system of navigation based on calculated distances from fixed base points has been developed and known as shoran. In the shoran system use is made of radio responder beacons having a known position. The beacons are of the type that when interrogated by a properly coded message immediately respond with a predetermined coded reply. The time elapsing between the transmission of the interrogating pulse and the receipt of the reply determines the air line distance of the vehicle from the beacon.

The automatic shoran is an all weather bombing system which includes measuring equipment based on the well-known shoran principle of beacon ranging. The equipment provides automatic navigation and bombing through an autopilot. The system not only includes an airborne digital computer, but extends the use of digital techniques to range measurement and range gating equipment.

The airborne digital computer is a general purpose serial, binary machine utilizing a magnetic drum memory. The range measurement equipment is a pulse-counting device incorporating a vernier interpolation principle to achieve the desired accuracy.

The accuracy of a digital computer is not determined by the nature of its elements, but only by the number of the basic elements employed. The choice of a given accuracy designates the number of binary digits that will be used within the machine. In this system the binary numbers are composed of 19 digits. This number was chosen so that the computation would be potentially more accurate than any of the input or output data. The computing element, therefore, will not be the limiting factor in the system accuracy.

The digital computer is composed almost entirely of repetitive electronic circuits. These circuits are constructed from standard components and, due to their repetitive nature, are well adapted to printed circuit and dip-solder techniques.

The use of a digital system will greatly simplify the field maintenance problem. Since there are only a few basic circuits, it is feasible to construct nonreparable assemblies. Only a relatively few assemblies must be stocked for field maintenance, and repair will be accomplished by discarding and replacing faulty subunits.

Ability to modify the problem solution allows the employment of the system to be altered, dependent upon the situation. If instrument errors are detected, it is quite easy to program correction factors, or if radical changes are required in bombing techniques they may be accounted for. This flexibility is highly desirable, both in tactical use and during system development and evaluation.

The digital computer has the ability to select alternative routines based on the magnitude of numerical information. As an example, the range information is checked to determine if it is reasonable when compared to the previously known position of the aircraft. If the data is not valid, either for this reason or others, then a dead reckoning routine is employed, rather than the normal position computation cycle.

Because a digital computer has the ability to make programmed decisions, it is possible for it to navigate an aircraft automatically through a series of way-points, both in approaching the target and in returning. The switch of guidance to the successive points is entirely automatic and it is feasible to program several dozen of these points. In field operation these points would be selected to insure that the aircraft would avoid all known heavily defended areas.

In some instances it may be desirable to provide a pilot on the craft or mount a television camera or other sensing devices on the craft and transmit intelligence to a pilot on the ground or a mother craft.

By a similar program technique, it is possible to bomb several targets in succession. The system can also include means for the pilot to select one of several alternate targets, or a succession of targets.

In the proposed system the computer will be loaded with target coordinate information, way-point coordinates, and bomb characteristics prior to the flight. It is not necessary to rely on estimated target area winds. During flight, the computer receives accurate positional information in the form of range measurement data, together with data from the compass, altimeter, and true airspeed instruments. From successive ground positions a very accurate ground velocity is computed. By using this velocity and the true airspeed vector, an accurate value for the wind is computed. If at any time range measurement information is lost due to jamming, interference, intentional radio silence, or any other cause, the computer can dead reckon very accurately. During a dead reckoning period the computer utilizes its previously computed value of wind, together with the instrument readings, to navigate the aircraft. Since the computer is continually receiving data from the aircraft instruments, it will continue to compute position despite aircraft maneuvers.

The normal period of time required for the solution of the problems of position, smoothing, prediction, guidance and data checking is about one-third of a second. Range measurement information is utilized by the computer at this rate; therefore, the ground beacon interrogation rate of this system will be much lower than previous shoran systems. Only in the target area is it essential to have maximum accuracy. Since the computer is controlling the interrogation rate, it is possible to program it so that regular periods of dead reckoning are forced in regions other than the target area. This would effectively reduce the pulse rate even more.

The end result of reducing the interrogation rate is to greatly increase the traffic handling capacity of the system. The pulse repetition rate of the ground transmitters is reduced to a point where their average power dissipation is not a limiting factor. The remaining limit is that of the probability of interference between many aircraft interrogating the same ground stations. The digital computer's decision ability is used again as a means of checking the received range data to determine if either interference or jamming has occurred. In either instance, if the data is not valid, the computer discards it and dead reckons.

The susceptibility of this system to jamming is quite low. The low repetition rate of the transmitters makes it quite difficult for the enemy to observe the airborne transmitter. The range gating provides some further degree of protection; however, the greatest protection is offered by the computer's checking ability. Detection of the aircraft would be difficult since the pilot can maintain radio silence when he desires.

No additional equipment is required to achieve automatic scrambling of the range measurement rate. Since this rate is under control of the computer, and since the computer dead reckons when interference occurs, automatic scrambling is accomplished by having the dead reckoning require less time than the normal computing cycle. The normal computation time is controlled by the computer, which in turn is related to the frequency of the power source, so no two planes will have exactly the same normal rate. To further insure that lock-on to another aircraft's signals will not occur, the computer is forced to dead reckon at regular intervals.

Each system in the air can identify its own range signals by these computer checks, therefore, it is not necessary for each system to have different coding signals. This greatly simplifies the coders and decoders in both the airborne and ground equipment. Standardization of these units would facilitate ease of maintenance and production.

The two range measurements are made in a serial manner with range gate data being provided by the computer. The receiver and time measurement equipment can be used for both range measurements so only one of each of these units need be used.

The memory and storage ability of the computer makes possible the recording of bomb damage assessment data without the addition of any equipment. At the time of bomb release, the heading, altitude, air speed, and position of the aircraft can be recorded in the computer memory. A magnetic drum memory is non-volatile, i.e., the information in it is not destroyed when the power is shut off, therefore this information will be available for inspection after the completion of the mission.

In adapting this system to reconnaissance it is not feasible to store all the desired data in the computer memory, since this would require the memory to be excessively large. The data on a reconnaissance mission would be processed by the computer and the results recorded on an auxiliary tape recording unit. This digital system would adapt itself very well to reconnaissance since the system could be programmed to automatically navigate through a series of way-points, thus very accurately covering the desired area. The use of a digital data recorder allows a large number of quantities to be recorded for each desired point.

The operational characteristics of the types of aircraft that employ an automatic digital shoran system dictate that this system must be carried external to the air frame. Not only is the internal space of these aircraft at a premium, but it is necessary to use these aircraft for multiple purposes. External mounting achieves this flexibility, since a system thus mounted could be detached when the aircraft is to be used for purposes other than all-weather bombing.

The physical shape of the external mount is that of a standard equipment pod. This is a reasonable aerodynamic form and is readily attached to the bomb shackles with which these planes will be fitted.

The digital shoran system requires sensing of the aircraft instruments. The sensing and conversion equipment would be located in the pod, however, transmission by servo systems from the instruments to the pod would require a small amount of power from the central system. This is necessary since the data transmission loop must be powered from a single source. The function of the system requires that the digital computer have data from aircraft compass, air speed, and altitude instruments. In addition, it is desirable to have yaw angle data if this is available.

The physical attachment of the system to the aircraft will require only the mechanical mounting to the bomb shackles and the electrical connection of a cable containing the instrument, control, and display signal wires.

The pilot will at all times be aware of the status of the mission. Shortly after take-off, a ready light will indicate that the system is in operation and may be engaged. The pilot will have a choice of either manual control following a PDI or completely automatic control with the system controlling the aircraft through autopilot. The pilot's indicators will show the way-point or target the plane is being guided toward and the remaining time-to-go to that point. An indicator will be showing whether the system is presently computing position from range information or dead reckoning. The release of the bombs will be made automatically; however, an interlock switch controlled by the pilot will be provided. A manual target selection switch will allow the pilot to choose between primary and secondary targets.

The dead reckoning ability, made possible by the computer's memory, gives rise to several tactical advantages. The frequency of ground beacon interrogation may be reduced far below that required with existing shoran systems without impairing the system accuracy. The pilot may maintain radio silence for sustained periods if it is desired. Susceptibility to jamming is greatly reduced, both because of the lower interrogation rate and because the digital computer can check the validity of the range measurement data. When interference from other aircraft is detected, scrambling of the interrogation rate is automatically accomplished by having the dead reckoning computation cycle require a length of time different from that of the normal cycle.

The ability to establish a number of navigation way-points in approaching and returning from a target is very useful. Heavily defended areas may be avoided and the approach to the target designated by appropriately chosen points. It is even conceivable to have the aircraft automatically follow rail or roadways by appropriately selecting way-points. This will result in the aircraft flying a series of straight lines approximating the curvature of these roads. The path of the aircraft will be a series of straight lines defined by these points since the system always navigates the aircraft to fly the shortest distance from where it is to the next point.

Generally the approach to the target will be fixed by the location of the last way-point. Since automatic control of the aircraft results in the shortest path between way-points or targets, the approach to the target will be essentially a straight line determined by the coordinates of the target and the last way-point. The pilot, however, can assume control of the aircraft at any time so that if evasive maneuvers become necessary, they may be taken. When automatic control is re-engaged, it will cause the aircraft to fly the shortest path from where it is to a release point. This effectively gives the pilot his choice of approach, if this becomes desirable.

With manual bombing systems it is necessary to have a sustained period of straight and level flight during the bombing run. This allows the operator to determine drift angle and ground velocity and to align the aircraft. In this completely automatic system the wind values and virtual target are being continually computed, despite the maneuvers of the aircraft. These computations continue regardless of whether manual or automatic control is being used. Thus, the time necessary to maintain straight and level flight is only a very few seconds. This affords the pilot the opportunity to take evasive maneuvers much closer to the target than would be possible with a manual system. In fact, accurate bombing can be done within five to eight seconds after completing a 180-degree turn.

When the system is used for reconnaissance it will be necessary to provide an auxiliary recording unit. This unit will be capable of recording a large amount of data concerning each desired point, since this data is all available from the computer in digital form. By using a digital tape recorder, data could be taken for an extremely large number of points. In setting up a reconnaissance mission, navigation way-points would be selected so that the aircraft would automatically and accurately cover the desired area. With each ground mapping photograph taken there would be an accurate record of position, air speed, heading, altitude, and any other desired data.

It is accordingly an object of the invention to provide an improved navigation system.

It is a further object of the invention to provide an automatic bombing system.

It is another object of the invention to provide a navigation system controlled by a digital computer.

It is still a further object of the invention to provide a system for increasing the number of aircraft serviced by a single group of beacons.

It is still another object to provide an accurate range measuring device utilizing a vernier interpolation principle.

It is another object to provide an accurate converter from an analog to a digital computer.

Other objects and advantages will be apparent from the following detailed description taken in conjunction with the accompanying drawing in which:

FIG. 1 is a block diagram of a system according to the invention;

FIG. 2 is a block diagram of the automatic range measuring equipment;

FIG. 3 is a graphical illustration of the range measuring operation;

FIGS. 4*a* and 4*b* are graphical presentations of the maximum error in the range measuring system;

FIG. 5 is a graphical illustration of station angle versus error factor;

FIG. 6 is a graphical chart of the lines of constant station or constant position error factors;

FIG. 7 is a schematic illustration of an instrument coupler;

FIG. 8 is a schematic illustration of a nonambiguous counter converter;

FIG. 9 is a block diagram of the shaft-positive-to-binary conversion system;

FIG. 10 is a schematic diagram of the comparator for the conversion system;

FIG. 11 is a graphical presentation of three dimension shoran geometry; and

FIG. 12 is a flow diagram for the computational routine.

An illustrative embodiment according to the invention comprises a plurality of fixed beacons **20**, at least two in number, and preferably arranged in spaced apart relation forming a base line substantially transverse to the normal direction of the flight path. The aircraft mounted equipment comprises a transceiver equipment **22**, a range measurement equipment **24**, auxiliary input equipment **26**, an input register **28** and a digital computer **30** providing control information to an autopilot coupler **32**, a bomb control **34** and in the event a pilot is on the craft a pilot display device **36**. The beacons **20** are standard shoran equipment containing a receiver **40**, a decoder-coder **42** and a transmitter **44**. Both the receiver **40** and the transmitter **44** are connected through a diplexer **46** to an antenna **48**. Usually a calibration system **50** can be connected by means of switch **52** into the beacon equipment to determine any operating errors therein.

The transceiver **22** includes the coder **54**, decoder **56**, the transmitter **58** and a receiver **60**. This transceiver equipment is identical with the heretofore used shoran transceiver equipment in order to use existing equipment that has been proven in use.

The range measuring unit **24** comprises a range register **70** which receives from arithmetic element **92** a number proportional to the anticipated range. A range gate **72** is connected to range register **70** to control which range signals are to be passed from decoder **56** to range measurement device **74**. The output of the latter device is applied to input register **28** which transfers the resultant range measurement to arithmetic element **92** of digital computer **30**. In addition to the range information, data from certain aircraft instruments are also made available to the digital computer. As shown in FIG. 1, airspeed, altitude, and heading readings taken from units **76**, **78** and **80**, respectively, are applied to shafts **77**, **79** and **81**, respectively, for conversion to binary quantities by means of converters **86**, **88** and **90**, respectively. The outputs of computers **86**, **88** and **90** are tied jointly to one of the input leads of input register **28**. When it is desired to have a yaw angle indication to increase the accuracy of the wind computation, the yaw angle indication, as from a unit **84**, may be shaft-to-binary converted in the same manner as the other instrument readings or may be used to directly modify the heading reading prior to conversion, as shown.

The digital computer **30** comprises an arithmetic element **92**, a drum memory system **94** and an automatic program control **96**. As mentioned previously, computer **30** is a serial binary general purpose computer, i.e., numerical information is represented as a time sequence of pulses in binary form. Digital computers are well known in the art, and one form of computer having characteristics readily suiting it to act in the capacity of computer **30** of the invention is described, for example, in chapter 11, page 333, FIG. 11–3, of "Arithmetic Operations in Digital Computers," by R. K. Richards, D. Van Nostrand Company, Inc., 1955. The subject matter of the referenced publication illustrates equipment applicable for use as the arithmetic element **92**, memory **94**, and automatic program control **96** which comprise the computer **30**. The computer elements are straightforward in their design so that further illustration is believed unnecessary and the manner in which computer **30** and the elements thereof may be practiced is disclosed to those skilled in the art. Program control **96** receives memory commands from the memory device **94** and the output of the arithmetic element **92** and issues output commands both to the input register **28**, the range measuring device **74**, the auxiliary input devices **86**, **88** and **90**, as well as the output devices, including the autopilot coupler **32**, the bomb control **34** and the pilot display indicator **36**.

Range measuring device **74** comprises a gate **100**, a unit pulse generator **102**, a fraction pulse generator **104**, a coincidence detector **106**, an Nth pulse generator **108**, a fraction gate **110** and a unit gate **112** connected through an or gate **114** to a unit counter.

Operation of the proposed system is illustrated in FIG. 3. Upon a command **116** from the digital computer to begin a range measurement, one of the one-megacycle unit pulses **128** is gated out through gate **100** to the coder **54** and pulse **118** is transmitted by the airborne transmitter. The selected unit pulse **128** also opens unit gate **112** and unit pulses are counted in a unit counter. The counting rate is one megacycle. The response signal **124** received on the aircraft by the receiver **60** from the ground beacon **20** is decoded by decoder **56** and is used to initiate a train of vernier or fraction pulses **122** from fraction pulse generator **104** whose period is longer than the unit pulse **128** period by one-eighth of the unit pulse period. Both the unit pulses **128** and fraction pulses **122** are detected for time coincidence in a coincidence detector circuit **106**. When the unit and fraction pulses are in time coincidence, pulse **128** closes the unit gate **112** and opens the fraction gate **110**. The unit counter stops counting unit pulses and both the unit counter and fraction counter begin counting fraction pulses. The counting rate is approximately 889 kilocycles. The fraction gate **110** is closed after the eighth fraction pulse **122** and the unit counter and fraction counter stop counting fraction pulses. Each unit count represents 1.0 microsecond (492 feet in range) and each fraction count represents 0.125 microsecond (61.5 feet in range). The excess count accumulated by the counters in this system represents 9 microseconds. Interpolation is only required at the end of measurement since the beginning of the measurement is in phase with the unit timing pulses.

A straightforward method of vernier interpolation could be used by making the fraction pulse period shorter than the unit pulse period by one-eighth of the unit pulse period. Unit pulses would be counted in the unit counter between the time of the transmitted and the received timing pulses. Fraction pulses would be counted in the fraction counter between the time of the received timing pulse and coincidence between the unit and fraction pulses. This would eliminate the Nth fraction pulse generating circuit in the proposed system. However, if the received timing pulse arrived in, or near, time coincidence with one of the unit pulses, an error of one microsecond in the unit count could result since the closing of the unit gate **112** cannot be made instantaneous. This error, which represents approximately 492 feet of range, could occur as much as 15 percent of the time. Thus, the present system which eliminates such gross errors is much more desirable even though additional circuitry is necessary.

The frequency stability required of the unit pulses is determined by the maximum range or time difference to be measured and the allowable error at this maximum. For this system, the unit pulse generator frequency stability should be ±8 parts per million for a range measurement error of less than ±15 feet at a range of 300 nautical miles. The frequency stability required of the fraction pulses is ±1 part in 300 to obtain a maximum error of less than ±13 feet of range. This permits use of a pulsed LC oscillator or ringing circuit for the generation of fraction pulses and a crystal controlled oscillator for the generation of unit pulses. The unit and fraction pulses which are detected for time coincidence are in the order of 0.125 microsecond wide. The coincidence detector **106** is able to differentiate between two 0.125 microsecond pulses spaced more than 0.125 microsecond apart, and two 0.125 microsecond pulses spaced less than 0.125 microsecond apart, resulting in a maximum range measurement error of less than ±31 feet.

Part of the range measurement equipment must also be used to measure the digital computer magnetic memory drum speed which forms the time base for velocity computations. This is accomplished by counting the number of one-megacycle (unit) pulses occurring between two pulses on the drum surface into the input register **28**. The computer performs the necessary computations to convert this count into a measure of the cycle time of the computer. No additional equipment is required.

Since the range measurement system uses pulse-counting techniques an inherent quantization error results. The magnitude of this quantization error is a function of the range being measured as shown in FIG. 4.

The result of a range measurement is the number of unit fraction counts stored in the computer input counter and register **28**. In the equations which are solved by the digital computer, it is assumed that each unit count represents K_1 microseconds and each fraction count represents K_2 microseconds. Simplicity of design and operation requires $K_1=2^nK_2$. In the range measurement equipment, the unit count consists of the whole number of periods of the unit pulse generator which are contained in the period between the transmitted pulse **118** and the received pulse

124. If the unit pulse period is not K_1 microseconds, then an error results and the magnitude of the error depends upon the number of unit counts and the difference between K_1 and the unit pulse period.

The fraction count represents the whole number of fraction pulse periods between the received pulse **124** and the previous unit pulse **128**. If either the fraction or unit pulse periods is incorrect, then an error results. The magnitude of the error depends upon the fraction count and the difference between the fraction and unit pulse periods and K_2. It is in the fraction measurement that the quantization error occurs. The magnitude of this quantization error is a function of both the unit and fraction pulse periods and the range being measured, as shown in FIGS. *4a* and *4b*.

Field tests of this range measurement equipment were made using existing ground stations and surveyed test sites. Results of these tests are given below:

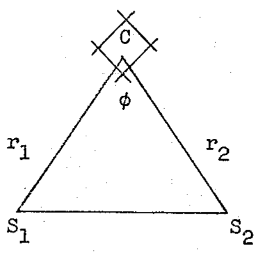
	Beacon 1	Beacon 2
True Range ft	27,192	55,108
True Range μsec	55.309	112.090
Meas. Range μsec	56.270	113.115
(Meas.)—(True) μsec	0.961	1.025

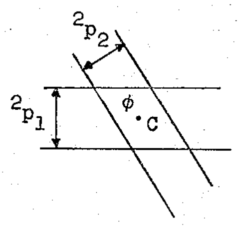
The difference between the true range and the measured range represents the zero range delay of the range measurement system. It includes receiver and transmitter, antenna lead, and range measurement equipment delays. This difference would be the same for both measurements if there were no error in either measurement. From the data above there is a total error of 0.064 microsecond which represents the sum of the errors in both measurements. Since the error in one measurement can be 0.0625 microsecond maximum due to quantization, this result is considered satisfactory.

Tests made in the field were compared with laboratory test data which substantiated that for every 62 feet change in true range the measured range changed a corresponding 0.125 microsecond.

It has been shown that if the position of a point is defined by two independent rectilinear (but not necessarily rectangular) coordinates, both subject to errors that are normally distributed, all the infinitesimal equal areas within which the point has some numerically specified chance of falling lie along an ellipse. All these ellipses are concentric and have the same eccentricity. Shoran ranges define coordinates of this sort over a small area and the theory may be applied to shoran fixes.

These error ellipses are centered at the center of an error parallelogram as shown below:





where

r_1=range to S_1 from C
r_2=range to S_2 from C
ϕ=station angle S_1CS_2 (crossing angle)
P_1=probable error in r_1
P_2=probable error in r_2

If the probable error in r_1 is equal to the probable error in r_2 and an error ellipse is chosen such that the chance is even that the true position is within it, then expression may be determined for the probable position error in terms of the station angle and the probable error in range. For practical purposes the ellipse is replaced by a circle with radius D.

$$D=\frac{1.625}{\sin\ \phi}p=P_{\mathrm{P}}$$

where

D=probable position error

p=probable range error

ϕ=station angle

P=probable error factor$=\frac{1.625}{\sin}$

FIG. 5 is a plot of normal distribution probable error factor versus station angle. The minimum probable error factor is 1.625 and occurs when the station angle is 90°. FIG. 6 shows lines of constant probable error factor or constant station angle. The solid circles show the probable error at different station angles. The smaller or inner dashed line represents the probable error factor for a base line of 100 nautical miles at a distance of 300 nautical miles, while the outer dashed line indicates the probable error factor for a base line of 75 nautical miles and a range of 300 nautical miles. The data at the left is the station angle of the error circles; the central figures on the error circles are the probable error factors; and, the right-hand figures are the standard deviation error factors for each angle. For a 100 nautical mile baseline, the probable error factor is 5 at a range of 300 nautical miles near the perpendicular bisector of the baselines. For a 75 nautical mile baseline and a range of 300 nautical miles, the probable error factor is 6.5.

For positions on the perpendicular bisector of the baseline and at least 2 baseline lengths away from the baseline, an approximate expression for the probable error factor may be written

$$P=\frac{5N}{3}$$

where N=number of baseline lengths away from baseline ($2>N>6$).

A block diagram of a suitable instrument coupler is shown in FIG. 7. The converter unit consists of a conventional servo follow-up system transmitter **140** and a follower **142** driving a mechanical binary counter **144**. The servo accurately positions the counter shaft **146** to correspond to the position of the instrument shaft **148**. A binary number corresponding accurately to the shaft position then appears, in parallel form, at the output terminals of the counter **144**, from whence it is parallel-set into the input register **28**.

The operation of the mechanical counter **144** can best be understood by first considering a version as shown in FIG. 8. Each digit of the counter consists of a cam operated switch **150**. When the switch is in the up position, the corresponding digit is a 0, and when the switch is down, the corresponding digit is a 1. The first cam **61** is directly driven by the counter shaft **146** and the cams are driven by a gear train **152** with a 2:1 reduction between successive stages. Examination of FIG. 8 will show that every half turn of the cam c_1 in the direction of the arrow causes an increase of one in the number contained in the counter.

It depends for its operation on the use of two switches per cam, spaced 90° apart on each cam except cam c_1. Since each cam has a 180° lobe, it is physically impossible for both of the switches to operate simultaneously; and by always reading the switch which is not in the process of changing, it is possible to eliminate all ambiguities. This is accomplished automatically by employing the configuration of switches representing the digits of less significance than the k^{th} to determine which of the switches on the k cam should be read.

The operation of the counter can best be explained by an example. As the counter is shown in FIG. 8, the output of each stage is a one. A small rotation of the input cam c_1 in the direction of the arrow, sufficient to cause the corresponding switch s_1 to operate, will cause the output of every stage to become a zero, without any of the other switches operating. If the input shaft **146** is rotated through an additional 180° in the direction of the arrow, the second cam c_2 will rotate through 90°, the third c_3 through 45°, etc. At that time, switch 1–A is in the H position, but due to the new position of cam c_2, the only change in counter output will be a one appearing in the first digit. If the input shaft is rotated through 360°, cam c_2 will be rotated through 180°, and cam c_3 through 90°, so that when switch 1–A goes to the L position, a zero will appear in the first digit, and a one will appear in the second digit, but there will be no change in the rest of the counter. In this manner, the operation can be traced as the input shaft **146** is rotated and it will be seen that the output is a binary representation of the number of half-revolutions described by the input shaft **146**.

The function of the diodes **160** is to prevent undesired short circuits when both switches of any stage are in the same position. Because transfer is accomplished by the action of switch S_{1-a}, the only ambiguity that might exist would occur when that switch is in the process of changing. At that time there is no output from any stage. This is detected automatically and any reading taken at this time can be rejected by the computer. The switches which are used in the counter are snap action so that in practice the correct reading is nearly always available.

In addition to the mechanical counter type of instrument coupler, a second type of coupler, entirely different in its operation, has been developed and is being used with the research model of the system. A block diagram of this shaft-position-to-binary conversion system is shown in FIG. 9.

This conversion scheme depends for its operation on the fact that if the two stator windings of a resolver **170** are excited by quadrature voltages, the phase of the voltage induced in the rotor is shifted from its reference position by an amount which is proportional to the angular displacement of the resolver shaft. By driving the two-phase excitation generator **172** from the memory drum **94**, the resolver output voltage may be referenced to the origin pulse. The time interval between the occurrence of the origin pulse and the next negative-going zero crossing of the resolver output voltage is an accurate indication of the angular position of the resolver shaft. This is measured by counting clock pulses during the interval.

Since the linearity of the system depends upon the resolver excitation voltages being in exact quadrature, being of equal amplitude, and having low harmonic content, it has been found desirable to isolate the generator from the resolver by an amplifier **174** designed to have low output impedance, minimum harmonic distortion, and minimum phase shift. The two-phase generator **172** itself is a rebuilt Reeves resolver type R–600 which has been modified to include a permanent magnet rotor. Both the Reeves type R–600 and type R–150 resolvers meet the linearity requirements for the resolver itself, the latter unit being the more desirable because of its small physical size. The over-all linearity of the system has been demonstrated to be within ±0.1 percent of full scale over the full range of rotation.

The negative-going zero crossing of the resolver output is detected by the multiar circuit of FIG. 10, whose function is to generate a pulse at the exact instant the input voltage reaches zero. The multiar will be seen to consist of a compensated diode voltage comparator **176** and a blocking oscillator **178**. The blocking oscillator tube **180** is normally conducting, but whenever the input voltage is positive, the comparator diode **176** is back-biased, the feedback loop is open, and no regeneration occurs. At the instant the input voltage goes negative, the diode conducts, completing the feedback loop and causing the oscillator

178 to generate a pulse. Following the pulse, the blocking oscillator 178 is cut off by the negative input voltage; hence no more pulses can be generated until the next negative-going zero crossing.

The purpose of the second half of the duo-diode is to compensate against heater voltage variations. However, variations in temperature and supply voltage, and variations in tubes, cause bias errors, whereby the comparator output curve is shifted slightly up or down. Tube changes have been shown to cause a maximum shift of ±0.17 percent of full scale, with the majority of the tubes tested causing a shift of less than ±0.12 percent.

Bias-type errors due to temperature variation may also be caused by changes in the reactance of the stator windings, changing the excitation current. This source of error may be minimized by the use of a feedback resolver, such as the Reeves type R–151, having dual stator windings. Negative feedback is applied from the auxiliary windings to the excitation amplifier, forcing the excitation current to remain in phase with the generator voltage.

The digital computer proposed for the computation and control element of this automatic shoran system is a general purpose computer. The logical steps that are to be followed in the solution of the navigation and bombing problems are stored in the memory 94 and are therefore susceptible to modification without equipment changes.

The computer to be used in the automatic shoran system has the following general characteristics:

(1) The computer accuracy has been chosen so that it is not a limiting factor in the system.

(2) It will have the flexible characteristics inherent in a general purpose computer.

(3) The size will be small enough to allow inclusion in a pod packaged system.

(4) The computer will not require an accurately controlled power source.

(5) Maintenance ease and accessibility will be achieved through the use of plug-in subassemblies.

The small size required dictates that the numerical data within the computer be handled in a serial manner. In this way the digits of a number are designated by a sequence of pulses spaced in time. This is opposed to parallel operation where the digits of a number are designated by pulses on individual lines all occurring simultaneously. The serial or sequential handling of digits allows all digits to be operated upon by a single element of the computer where the parallel system requires duplicate equipment for each digit. To further minimize the amount of equipment required, numbers are represented by a straight binary code. This allows the minimum equipment for both the arithmetic circuits 92 and for the memory 94. Since there is little human intervention in the system, the use of a straight binary code imposes no disadvantages.

The amount of data and the number of orders that must be stored in the computer 94 dictate that a magnetic drum memory be used. This type of memory is the most economical known at the present time for storing many quanities in a small space.

The economy of storage space allows the orders or problem sequence to be stored in the memory. Since the problem to be solved is designated by this sequence of stored orders rather than by any physical equipment, it is very easy to make problem changes. This feature is the reason for the adaptability of digital computers. If at any time it is desirable to change either the problem being solved or the manner in which it is being solved, this can be done by simply recording a new set of instructions in the memory. It is of importance to note that a complete problem change requires no equipment change.

An airborne computer must have a nonvolatile storage system, otherwise any momentary power failure would cause the loss of all memory data. A magnetic drum is nonvolatile since data storage is in the form of magnetized spots on the drum surface.

The requirement of minimum size indicates, therefore, that the digital computer shall be a serial, binary machine with a magnetic drum memory. From a study of the accuracy of the input data, range desired, and the required system accuracy, it is desirable to have 19 binary digits and one sign digit within the machine. This provides a potential computation accuracy (about 1 part in 500,000) in excess of the input data accuracy. Past experience, however, has shown that this excess potential accuracy is highly desirable.

A study of the maintenance and production problems indicates that the computer should be built in the form of a limited number of plug-in assemblies. Due to the repetitive nature of the circuits in a digital computer, there need be only a small number of different assemblies for maintenance purposes.

The arithmetic element 92 of the digital computer performs the actual processes of addition, subtraction, multiplication and division. It is proposed that in addition to these operations and their associated transfers, several other automatic operations be included. Based on the problem study and past experience, square rooting, absolute value transfers, and shifting operations will be included.

During the performance of the arithmetic operations, it is necessary to make continuous reference to as many as three numbers. During multiplication, for instance, it is necessary to repeatedly use the multiplier, the multiplicand, and the partial product. Previously, static vacuum tube shifting registers have been used for the temporary storage of these quantities. It now seems feasible to replace this large number of tubes with special recording heads on the magnetic memory drum. These heads will each allow one number to be circulated, as in a delay line, thus making it continually available for the arithmetic operations.

The magnetic drum memory will provide storage space for 1792 orders and 462 numbers. There will be 32 order heads with 56 sectors around the drum. Each sector will be capable of storing 20 binary digits with one digit space between each sector. Six number heads will be used for the storage of constants. The computer can read information from these heads, but the information cannot be changed except by external means. In the same manner, the order information can only be changed by external means. These internally nonwriting heads are used both to reduce the airborne equipment and to prevent the accidental destruction of any of this information.

Two number heads are provided which are capable of both reading and writing. The two bands associated with these heads act as the scratch-pad memory for storage of the intermediate results of computation. To help minimize the solution time of the problem, two seven word-time circulating registers are provided. A number stored in one of these registers will be read and rewritten every seven words times, thus providing very fast access.

In addition to the above mentioned memory storage and the three one-word circulating registers for the arithmetic element, several heads will be used to provide the timing pulses for the computer.

The automatic program control 96 must control the selection of orders from the memory 94, interpret these orders, and instruct the elements of the computer to carry out the designated operations. The computer uses a modified two address code, i.e., each order contains the address of an operand and the address of the next order. To make it possible to designate two addresses and an operation in one order, a relative address code is used. The address of the operand is not designated specifically by band and absolute sector, but rather by the band and the number of sectors away from the present location. Similarly, the location of the next order is designated by the number of sectors from the completion of the operation to the desired order. The band information in an order designates both the band of the operand and the band of the next order. There are 32 order bands and only 8 number bands; therefore, several order band designations will be used for each number band. There will be six order band designations for each of the two seven-word circulating registers, four order band designations for each of the two scratch-pad bands, and two order band designations for each of the six constant bands.

The twenty digits of an order will be used to designate the following information:

(1) The first five digits will designate the operation to be performed.

(2) The second five digits will designate the band of the operand and the next order.

(3) The next five digits will designate the number of sectors from the one containing this order to the one containing the operand.

(4) The last five digits will designate the number of sectors from the end of the operation to the sector containing the next order.

The following is an abbreviated list of the operations performed by the computer:

(1) Add
(2) Subtract
(3) Multiply
(4) Divide
(5) Square root
(6) Tranfer from memory to arithmetic element (A.E.)
(7) Transfer from A.E. to memory
(8) Transfer absolute value from memory to A.E.
(9) Transfer from input to A.E.
(10) Transfer from A.E. to output
(11) Measure range No. 1
(12) Measure range No. 2
(13) Measure instrument readings

This is only a partial list since most of the functions from 6 through 13 require several different operations. A complete list of these including all the input and output operations would be greater than the 32 possible with the allowed five binary digits. Since the input and output operations do not involve reference to the memory, the band information for the operand has no function. This band information is used at these times to modify the operation, thus generating a possible 32 input-output operations from each basic operation.

The relative address order system is useful in coding problems for minimum solution time. The coder knows exactly what length of time each of his orders requires, and the magnitudes of the numbers designating the sectors to operand and next order are an indication of the program efficiency. Since the orders are not listed sequentially in the memory, insertion or deletion of orders is quite simple.

The proposed airborne digital computer is based on the experience gained in constructing and testing previous airborne digital computers.

The design of the autopilot coupler **32** for the proposed digital automatic shoran system will be dictated to a very large extent by the characteristics of the autopilot selected. There are, however, certain fundamentals which it may be assumed will be applicable.

A digital computer has several characteristics which must be given careful consideration whenever it is to be incorporated into a control system. The computer output is quantized in time and magnitude, and may at times be subject to large discontinuities which render the signal unsuitable for direct control of the aircraft without filtering. Such filtering inevitably introduces a time lag which, together with the additional lag due to the finite iteration time of the computer, tends to cause instability in the control system. Consequently, a successful digital computer-to-autopilot coupler must be something other than a device to convert instantaneously the binary output of the computer to the appropriate analog and apply it as a heading reference to the autopilot.

The autopilot coupler which was developed for the Digitac system represents one successful solution to the problem, the basic principles of which are very likely to prove applicable for use with other autopilots. Autopilot coupler **32** converts the binary steering signal from automatic program control **96** to a corresponding control signal in another form, such as analog, by which the course of the aircraft is modified through the action of the autopilot. An autopilot coupler suitable for use in the present invention as a digital-to-analog converter is disclosed in United States Patent No. 2,932,471.

The E-6 autopilot, for which the Digitac coupler was designed is a coordinated, precision type autopilot which receives its heading input from a Gyrosyn compass by means of a pair of synchros. Therefore, by interposing a differential synchro between the compass and the autopilot, it is possible to add algebraically a variable increment to the heading reference, and thus control the heading which the autopilot will follow. This is the basis of the coupler system used.

The basic elements of the coupler are:

(1) The differential synchro, referred to above, driven by a bi-directional notching motor.

(2) A counting-shifting register, into which steering signals are shifted from the computer, and wherein they are "counted down" by a series of count pulses.

(3) A variable frequency pulse generator.

(4) Appropriate gating, synchronizing, and delay circuitry.

In operation, a binary steering signal representing the computed heading error is shifted into the register once each computer cycle. A train of pulses is then applied to the count input of the register, counting the steering signal down to zero; and simultaneously to the notching motor, rotating the differential synchro ⅕ degree for each count. Whenever the number in the register reaches zero, the train of pulses is automatically shut off. The repetition rate of the pulse generator is made roughly proportional to the heading error, up to a maximum of 12 degrees. In the event that the steering signal indicates a heading error of over 12 degrees, as in a programmed turn, the coupler detects an overload condition and, by operating the notching motor at a higher rate, drives the autopilot heading potentiometer against its limit stop. This rolls the aircraft into a fixed bank angle of 20 degrees, which is maintained until the heading error is reduced to 12 degrees. The count pulses are then interrupted long enough for the aircraft to straighten out on the desired heading.

In the normal mode of operation, the maximum rate of heading correction is low enough to insure that no instability will result from the computer delays mentioned above. At the same time, direct analog heading feedback is supplied to the autopilot, insuring that the stability of the autopilot-aircraft combination will remain unimpaired.

The position of the aircraft is to be expressed in terms of a Cartesian frame fixed relative to the earth. The origin O is chosen at some point at sea level, with z axis **202** vertical, y **204** axis north, and x **206** axis east. For greatest accuracy in the neighborhood of the target T and for maximum simplification of bombing equations, the origin O is placed at, or near, the vertical projection of T onto sea level. The measured quantities which determine the position of the plane A are (r_1, r_2, l) where

r_1=slant distance of airfraft from slave S_1,
r_2=slant distance of aircraft from slave S_2,
l=altitude of aircraft above sea level.

The problem is to obtain the Cartesian coordinates (x, y, z) of the aircraft from these quantities (see FIG. 11). Assume that the earth is a sphere. Let

(x_1, y_1, z_1)=cordinates of S_1
(x_2, y_2, z_2)=coordinates of S_2
a=radius of the earth

Then the equations relating (x, y, z) and (r_1, r_2, l) are

$$\left.\begin{aligned}(x-x_1)^2+(y-y_1)^2+(z-z_1)^2&=r_1^2\\(x-x_2)^2+(y-y_2)^2+(z-z_2)^2&=r_2^2\\z=l-\frac{x^2+y^2}{2a}&\end{aligned}\right\}\quad(1)$$

The first two equations are exact; the third is a very close approximation in which second order terms in z/a and l/a are justifiably ignored relative to the retained terms in the third equation (after division of both sides by a).

A ground calculation is necessary for the determination of the slave coordinates (x_1, y_1, z_1) and (x_2, y_2, z_2). Let

λ=longitude
ϕ=latitude
l=altitude

Let the subscripts 0, 1, 2, attached to these quantities refer to the origin, S_1 and S_2, respectively. The longitude is taken in the range $0° \leqslant \lambda < 360°$ and is measured west of Greenwich; the latitude is taken in the range of $-90° < \phi < 90°$ and is measured from the equatorial plane. Then

$$\left.\begin{aligned}x_1&=(a+l_1)\sin(\lambda_0-\lambda_1)\cos\phi_1\\y_1&=(a+l_1)[\cos(\lambda_0-\lambda_1)\cos\phi_1\sin\phi_0-\sin\phi_1\cos\phi_0]\\z_1&=-a+(a+l_1)[\cos(\lambda_0-\lambda_1)\cos\phi_1\cos\phi_0+\sin\phi_1\sin\phi_0]\end{aligned}\right\}\quad(2)$$

with a similar formula for (x_2, y_2, z_2) in which the subscript "1" is replaced by "2."

The method proposed for position determination during the navigational phase is an iterative technique. It utilizes the last computed position and other accumulated data to obtain a predicted position for use in the next iterative solution. This is the best method since it meets all of the above objectives most closely. Initially starting with essentially arbitrary position coordinates, an accurate solution is obtained after several iterations. Therefore, each iteration provides accurate positional information.

At the beginning of each computational cycle, the computer predicts the position of the aircraft at the time during that cycle when the range time measurements will be made. The following formulas are used:

$$\bar{x}_n=x_{n-1}+v_{gx}^{n-1}\cdot\tau^{n-1}\quad(3)$$

$$\bar{y}_n=y_{n-1}+v_{gy}^{n-1}\cdot\tau^{n-1}\quad(4)$$

$$\bar{z}_n=z_{n-1}+(z_{n-1}-z_{n-2})\quad(5)$$

$$\bar{r}_{1_n}=\sqrt{(\bar{x}_n-x_1)^2+(\bar{y}_n-y_1)^2+(\bar{z}_n-z_1)^2}\quad(6)$$

$$\bar{r}_{2_n}=\sqrt{(\bar{x}_n-x_2)^2+(\bar{y}_n-y_2)^2+(\bar{z}_n-z_2)^2}\quad(7)$$

where

n=superscript or subscript "n" denotes quantities observed or computed during the nth computational cycle. Similarly, "$n-1$" refers to quantities from the last cycle before the nth cycle.
$\bar{x}_n$, $\bar{y}_n$, $\bar{z}_n$=the predicted coordinates of the aircraft.
x_{n-1}, y_{n-1}, z_{n-1}=smoothed coordinates of the aircraft, known from the last cycle.
v_{gx}^{n-1}, v_{gy}^{n-1}=components of ground velocity.
τ^{n-1}=time required for one computational cycle.
$\bar{r}_{1_n}$, $\bar{r}_{2_n}$=predicted slant ranges of aircraft from slaves S_1 and S_2 respectively.
x_1, y_1, z_1=coordinates of slave S_1.
x_2, y_2, z_2=coordinates of slave S_2.

Thus, the predicted x and y are obtained from the last position plus the ground distance travelled in one iteration time. The difference between the past two coordinates, either for x or y, is not used for prediction since it would give a straight line prediction and would not take into account any changes in direction. The prediction of z requires only the extrapolation of the past two known points as it is a slowly varying quantity and adequate accuracy is attained.

The predicted slant ranges $\bar{r}_1$ and $\bar{r}_2$ are now used to compute the predicted two-way range times to the beacons. These times are then modified to produce time quantities that are used in setting the range gates for the measurement of the range times.

$$t_{1R}^n=\frac{2\bar{r}_{1_n}}{v_p}+(\Delta T-\Delta G)\quad(8)$$

$$t_{2R}^n=\frac{2\bar{r}_{2_n}}{v_p}+(\Delta T-\Delta G)\quad(9)$$

where

t_{2R}, t_{1R}=time quantities used in setting the range gate for the measurement of range time from slaves No. 1 and No. 2, respectively.
ΔT=correction for known slave station delay, aircraft transmitter and receiver delays, and fixed excess unit count.
ΔG=time allotted between the opening of the range gate and the expected time of arrival of the signal from the beacon; ΔG allows for transient conditions while the range gate is opening.
v_p=velocity of propagation of the R-F signal.

After

$$t_{1R}^n$$

is computed, it is sent to the range gate control register; the computer then directs the time measurement equipment to measure the range time to the first beacon. During the period required for the measurement of the first range,

$$t_{2R}^n$$

is computed. The first measured range is then transferred into the computer; and

$$t_{2R}^n$$

is sent out to the range gate control register with the order to measure the second range time following immediately. After a period of time long enough to allow maximum range measurement, the second range is transferred into the computer.

The measured range times must be corrected for the fixed delays in the beacons and aircraft equipment:

$$t_{1c}^n=t_{1m}^n-\Delta T\quad(10)$$

$$t_{2c}^n=t_{2m}^n-\Delta T\quad(11)$$

where

t_{2c}, t_{1c}=range times from beacons Nos. 1 and 2, respectively, corrected for fixed equipment delays.
t_{1m}, t_{2m}=measured range times from beacons Nos. 1 and 2, respectively.

Other symbols as defined above.

The calculation of

$$t_{1c}^n$$

is carried out during the period when

$$t_{2m}^n$$

was being measured;

$$t_{2c}^n$$

is calculated as soon as

$$t_{2m}^n$$

is available.

Before the corrected range times are converted to ranges and used in the computation of position, they must undergo a number of checks. The first check is against the minimum range time allowable in the system; this provides a safeguard against zero readings due to failure in the range measurement equipment. That is, the computer checks to be sure that

$$t_{1c}^{n}-t_{\text{min.}}\geq 0$$

$$t_{2c}^{n}-t_{\text{min.}}\geq 0$$

The second check is against the maximum range time allowable; this rejects the time reading that would be made if no beacon response arrived during the range gate period. The computer checks to see that

$$t_{\text{max.}}-t_{1c}^{n}\geq 0$$

$$t_{\text{max.}}-t_{2c}^{n}\geq 0$$

If either of the range times fails to pass one of the first two checks, it is rejected completely and hence need not be subjected to the third check; it also is not stored for the comparison with the range time from the last cycle to make certain that the change in the measurement does not exceed a bound that depends on the time for one cycle and the maximum velocity of the aircraft.

The following inequalities must hold:

$$|t_{1c}^{n}-t_{1c}^{n-1}|<t_B$$

$$|t_{2c}^{n}-t_{2c}^{n-1}|<t_B$$

where t_B=the maximum expected change in range time from one cycle to the next. Generally, t_B will be on the order of 2 to 4 microseconds.

After

$$t_{1c}^{n}$$

is subjected to the third check, it is stored for use in the third check on the next cycle; the same statement holds for

$$t_{2c}^{n}$$

To be accepted as valid readings for use in the computation of position, both range times must pass all three checks. Since the third check imposes the condition on each range time measurement that the last measurement and the current one must agree within a narrow bound, it is necessary to obtain correct values of the range times to both beacons on two successive cycles before they will pass the third check. This implies that interfering signals would also have to lie within the same narrow bound on successive cycles to pass check number three.

If either measurement fails to pass all the tests, the computation follows a dead reckoning procedure (see below). In FIG. 12 a flow diagram for the computational routine is given. The dead reckoning routine is the left branch, while the normal routine is shown on the right. In dead reckoning, only the predicted values of position are used, since there is not a complete set of time data available for the computation of new coordinates.

If the checks show that the range time measurements are reasonable, the corrected times are converted to range measurements and a position solution is then computed by means of Equation 1. The time-to-distance conversion equations are:

$$r_{1n}=\frac{v_D}{2}\cdot t_{1c}^{n} \qquad (12)$$

$$r_{2n}=\frac{v_D}{2}\cdot t_{2c}^{n} \qquad (13)$$

where r_1, r_2=computed slant ranges from aircraft to beacons Nos. 1 and 2, respectively.

The heading input is checked, corrected for magnetic variation, and used to compute the x and y components of the air velocity. Before the later computation may be completed, however, the air speed must be similarly checked for reasonableness, corrected for any instrument error, and then properly scaled for use in this computation.

The calculation of ground velocity components utilizes position differences, wind computation, smoothing, air velocity components, and the time taken for a complete computational routine in the following manner:

Preliminary ground speed components are obtained by dividing the differences between the present and the previous position by the routine time. These ground speed components are checked against upper bounds, and if either one of them is too large, the previous wind velocities are used. If they are both within bounds, preliminary wind components are then computed by taking the differences between the preliminary ground velocity components and the air velocity components obtained above. These wind components are checked against an upper bound. If either of them is out of bound, the computer changes its position prediction as discussed below. If they are within bounds, they are heavily smoothed with past smoothed wind velocities to obtain new wind velocity values.

The purpose of the whole system is to steer the aircraft to a predetermined destination, or to a series of destinations whose coordinates have been provided to the computer. The computer is also provided with information indicating whether each destination is to be a "way point" or a "target." If the destination is a way point, the aircraft is to be steered over the way point and directed to the next destination. If the destination is a target, the aircraft is to make a bombing run on the target, drop its bombs and then go on the next destination.

A "steering signal" is supplied by the computed to the autopilot coupler for automatic control of the aircraft and to the Pilot's Director Indicator for manual control of the aircraft.

The distance from the aircraft to the bomb release point is computed during each cycle; this distance is divided by the ground velocity to obtain the time-to-go until bomb release. In the case of a waypoint, the distance and time-to-go are calculated with respect to the coordinates of the waypoint. The distance is displayed on an indicator; the time-to-go is used to determine when the functions preparatory to the bombing run should be performed, as well as the correct time for the computer to enter the bomb run routine.

The time-to-go is checked against a specified value; when t_g becomes less than this value, the computer enters the bomb run routine. During the bombing run, complete ballistics data are computed to assure that any changes in flight conditions occurring in the last few seconds before entering the bombing run are taken into account in the computation of the coordinates of the bomb release point. The time-to-go to the bomb release point is again computed, utilizing the latest ballistic data as well as allowing for the time required for the bombing run calculations themselves. The computer then enters a timing sequence in which the computer measures off the time-to-go with a high degree of precision. The computer then sends out the bomb release signal and immediately enters a subroutine which selects coordinates of a new destination for use in the main program. In the case of a waypoint, this subroutine is entered immediately after the distance to the waypoint drops below a specified value. In either case, after the target change subroutine, the computer returns to the start of the main routine.

Instead of performing all the computations in the normal routine, the computer will enter a dead reckoning routine in case either:

(1) One or both of the time measurements fails to pass one or more of the three validity checks, or

(2) The dead reckoning tally reaches a predetermined value and forces dead reckoning to occur.

In dead reckoning, the predicted position as given by Equations 3 to 5 is taken as the position of the aircraft. The computer detects a bad time reading, or the critical value of the dead reckoning tally, after Equation 11 has been solved. The equations used for normal positional computation, are then omitted from the dead reckoning routine.

The computations for true air velocity components and routine time, are included in the dead reckoning routine. Since no new position data are available, the rough ground velocity components cannot be computed; hence, no new wind velocities can be computed. Equations for smooth ground velocity components are included in dead reckoning; the past smooth wind velocity components are used in these equations. Any changes in the air velocity components are, therefore, reflected directly as changes in the smooth ground velocity components. Equations for steering signal and time-to-go, are also included in dead reckoning.

The computation time saved by the omission of many of the normal routine computations in dead reckoning is utilized for the computation of ballistic data. Thus, the coordinates of the virtual target (used in steering) and of the bomb release point (for time-to-go) are adjusted for any change in altitude and wind velocity since the last ballistic computation.

The dead reckoning tally is a counting arrangement in which a stored number is checked and then increased by 1 on each normal cycle following a dead reckoning cycle until the number reaches some predetermined value. On the following cycle, the check of this tally tells the computer that the critical value has been reached, and this forces dead reckoning to occur. The dead reckoning tally is reset to 0 on each dead reckoning cycle.

The primary purpose of forced dead reckoning is to insure periodic recomputation of the ballistics data. However, the length of the dead reckoning cycle differs from that of the normal cycle because of the need for scrambling when interference with the range time occurs. Hence, the periodic forced dead reckoning has another desirable effect; it acts as a second safeguard against the possibility of locking onto the beacon responses to another aircraft for a period exceeding the time between forced dead reckoning cycles. A lock-on condition of this kind has a very low probability of occurrence without forced dead reckoning, the probability of the lock-on lasting for more than the period between forced dead reckoning cycles is, therefore, extremely low.

The number of normal cycles between forced dead reckoning cycles might, for example, be chosen as 32. Then the time between forced dead reckoning routines would be from 11 to 16 seconds, depending on the length of the normal routine.

Since the time required for a dead reckoning cycle differs from that for a normal cycle, the value of the routine time (τ) used for the prediction of position and calculation of rough ground velocities on the following cycle should be adjusted for this difference. This is accomplished by changing the value of τ computed and stored during the dead reckoning cycle. Every routine makes use only of the τ measured on the preceding cycle; thus, the proper τ is used in every case. For a normal routine τ of .5 second, the τ for dead reckoning would approximate either .4 second or .6 second, depending on the time required for ballistics. The important thing is that the τ's differ by a time that results in effective scrambling.

When the computer enters the dead reckoning routine it checks the bomb tally to determine whether the guidance point is a waypoint or a target. If it is a waypoint, the computer adjusts the x–y coordinates of the waypoint. The quantities $\sin \eta$, $\sin \xi$, and $\cos \xi$ are constants for the particular waypoint in a fixed coordinate system, and hence can be stored as constants in the computer memory before flight. For a waypoint, the coordinates of the virtual target and the bomb release point are set equal to the adjusted coordinates of the waypoint. This assures that the aircraft will be steered directly toward the waypoint. If the value of the bomb tally indicates that the guidance point is a target, the computer solves the equations for the ballistic quantities and the bomb coordinates.

The time of fall, $\bar{t}$, and trail time, β, are functions of altitude and air speed and may be approximated by algebraic equations which then may be stored in the computer.

When d^n, the distance to the bomb release point in the case of a target, becomes less than a predetermined value, the computer goes into the bomb run routine. In this routine no further data are taken into the computer, and no steering signals are generated by the computer. All computations are based on quantities in the computer from the last cycle before entering the bomb run routine.

First the ballistic quantities and bomb coordinates are computed by the computer. The time-to-go to the bomb release point is now computed making use of the latest bomb coordinate data. Since the data used in this computation are from the last cycle preceding the bomb run, the value of time-to-go to the bomb release point computed is the time from the point in the preceding cycle when time measurements were made. However, time has elapsed since that point; namely, the time for the part of the nth cycle following time measurements, plus the time for the bomb run computations. Call this elapsed time $p.\tau^n$ where τ^n is the value of routine time stored in the preceding cycle. The value of p depends on whether the last cycle was a dead reckoning cycle or a normal cycle. Thus each normal or dead reckoning cycle must store the value of p for reference in the bomb run routine. The quantity $p.\tau^n$ is subtracted from the time-to-go to obtain the remaining time-to-go after the completion of the bomb run routine. Provision must also be made for possible delays in the operation of the bomb racks, $\Delta\tau$. This gives τ_{cd}°, the actual time-to-go from the completion of the bomb computations (including all the computations up to the start of "count down") to the time for the bomb release signal. The computer is now used as an accurate time measurement device in the bomb run timing routine. τ_R, the time required for one drum revolution, is computed by dividing τ^n by N, the number of drum revolutions required for the previous cycle. As was the case for p, N depends on whether or not the last cycle was a dead reckoning cycle or a normal cycle and hence must be stored by the preceding cycle. τ_{cd}° is placed in a register in the computer and, once each drum revolution, the time for that revolution is subtracted. The number remaining in the register is checked to determine if it has become zero or negative. If it is still positive, the process is repeated. If it is zero or negative, the bomb release signal is sent out. Thus, the maximum time error in the count down process is slightly less than the time required for one drum revolution, τ_R. This is less than .01 second. As soon as the bomb release signal has been sent out, the computer enters the target change subroutine.

For purposes of exemplification a particular embodiment has been shown and described according to the best present understanding thereof. However, it will be apparent to those skilled in the art that various changes and modifications in the construction and arrangements of the parts thereof may be resorted to without departing from the true spirit and scope of the invention.

What is claimed is:

For use with a system having a master station including an interrogating transmitter, a slave section responsive to interrogation from said interrogating transmitter and a receiver responsive to a response from said slave station, a range measuring device comprising a source of unit pulses, a source of fraction pulses, a start gate controlled by a unit pulse and a command pulse, a unit pulse gate, said start gate controlling transmission of an interrogating pulse and opening said unit pulse gate to start counting of unit pulses, a coincidence detector, a fraction pulse gate, means responsive to an answer pulse to apply said fraction pulses to said coincidence detector, said detector being responsive to coincidence of a unit pulse and a fraction pulse to close said unit gate and open said fraction gate, said fraction gate closing a predetermined number of fraction pulses after receipt of said answer pulse, and a binary register counting said unit pulses and said fraction pulses.

References Cited in the file of this patent

UNITED STATES PATENTS

2,665,410	Burbeck	Jan. 5, 1954
2,665,411	Frady	Jan. 5, 1954
2,932,471	Exner	Apr. 12, 1960

OTHER REFERENCES

"An Analog-to-Digital Converter," by A. D. Scarbrough. Trans. of the I.R.E. Professional Group on Electronic Computers, September 1953, vol. EC–2, No. 3, pages 5–7.

Convention Record of the I.R.E., 1953 Convention, part 7, pp. 1–5.

Convention Record of the I.R.E., 1954 Convention, part 5, pp. 66–76, and 174–177.

"The Digitac Airborne Control System," by Burbeck, Bolles, Frady and Grabbe. Trends in Computers: Automatic Control and Data Processing. Proceedings of the Western Computer Conference, April 1954, pp. 38–43.