April 20, 1965 W. H. PICKERING ETAL 3,179,355

GUIDANCE AND CONTROL SYSTEM

Filed Nov. 1, 1962 3 Sheets-Sheet 1

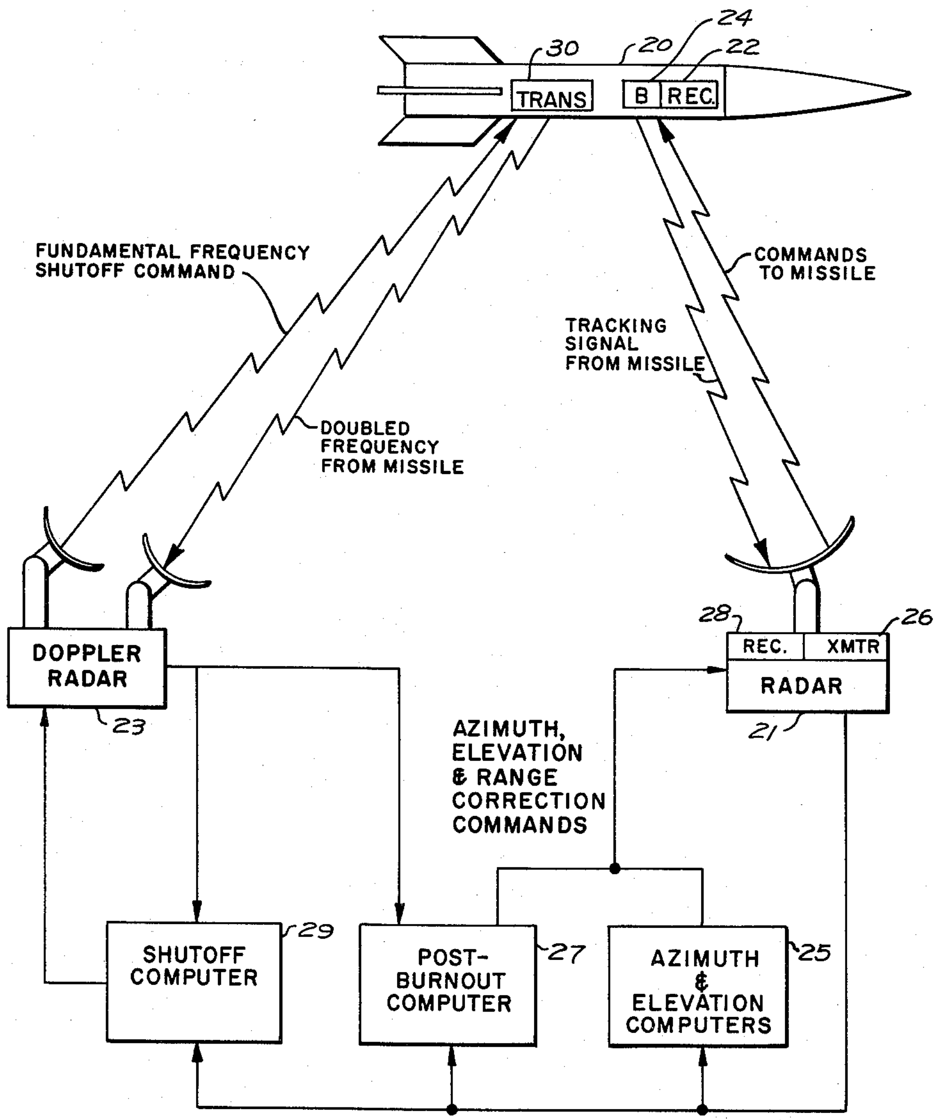

Fig. 1

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Filed Nov. 1, 1962 3 Sheets-Sheet 2

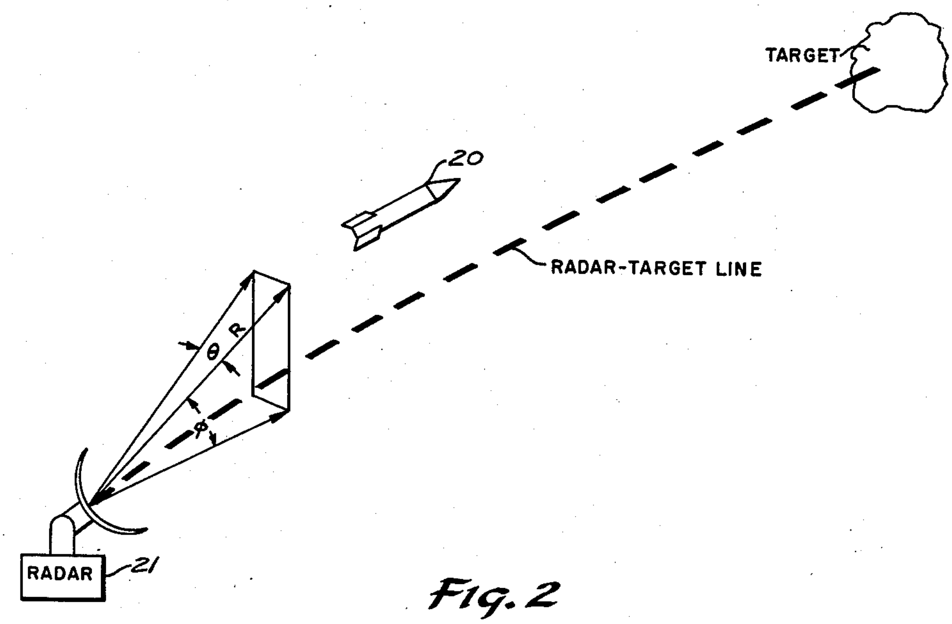

Fig. 2

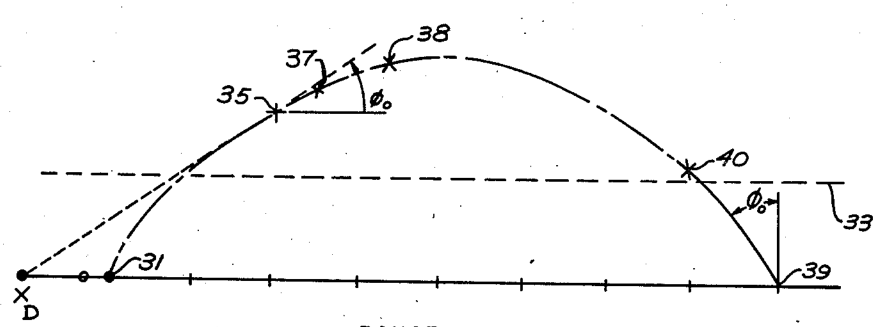

Fig. 3

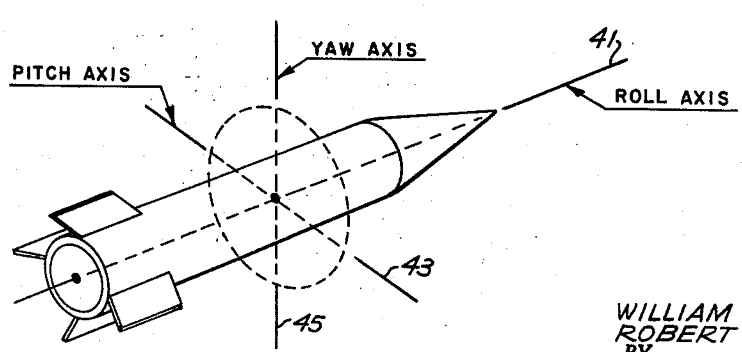

Fig. 4

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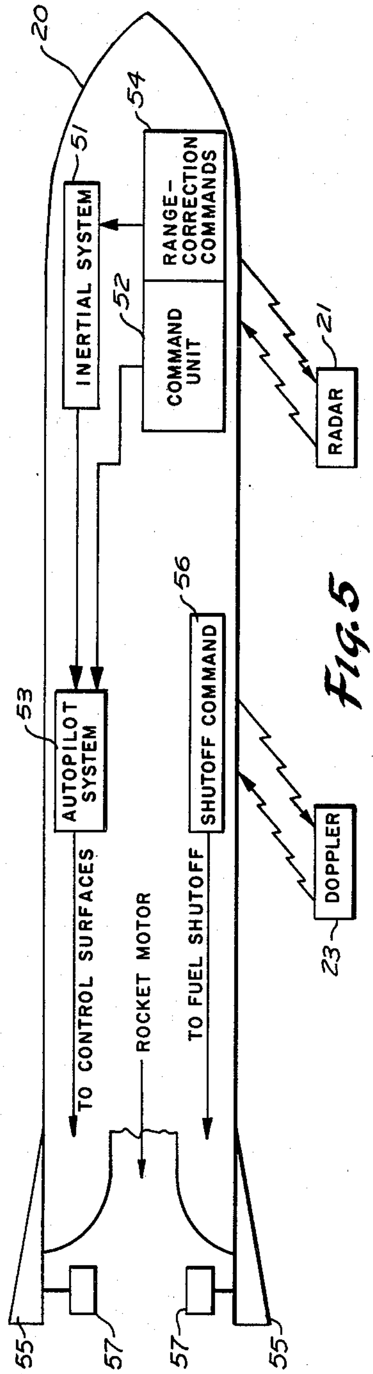

Fig.5

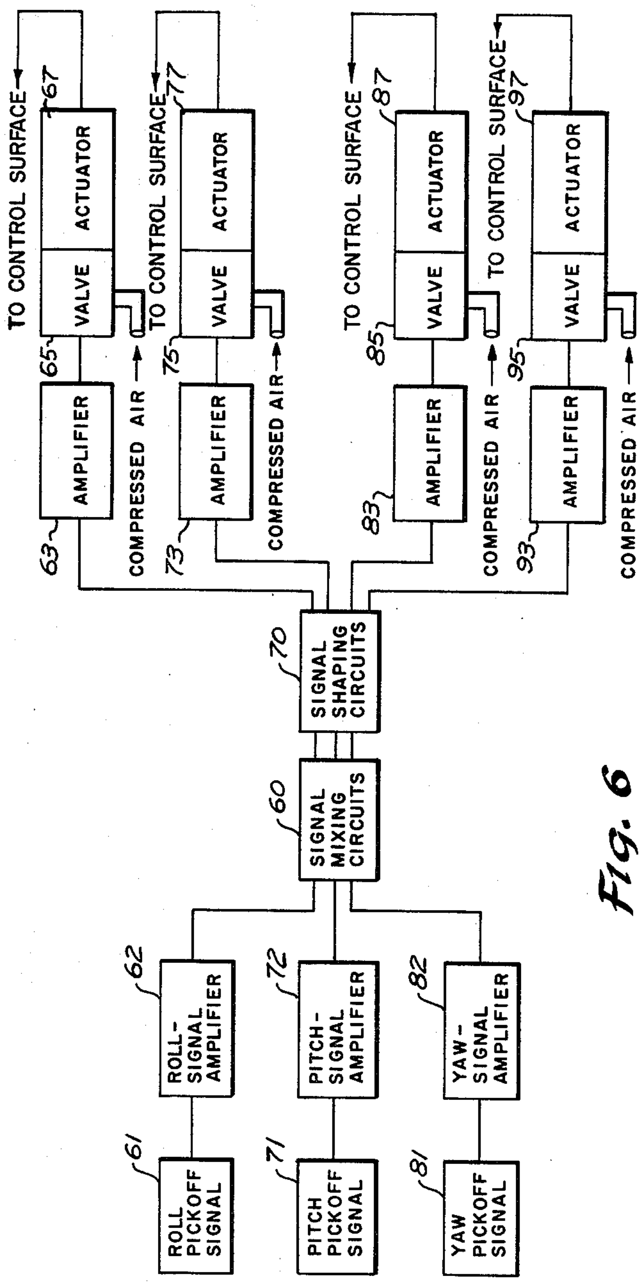

Fig. 6

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GUIDANCE AND CONTROL SYSTEM

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3 Claims. (Cl. 244—14)

The invention described herein may be manufactured and used by or for the Government for governmental purposes without the payment of any royalty thereon.

This invention relates to guidance systems and more particularly to a range-correction type guidance system for use with ballistic missiles.

A major problem in the development of ballistic missiles has been finding a suitable guidance control means for substantially eliminating target error. Such a guidance system must incorporate some type of trajectory-measuring equipment to provide information for accurately controlling the desired missile flight path. These measurements could be made either by air-borne, all-inertial elements, or by a ground-based radio system, or by some combination of the two.

Another consideration in the development of a more accurate ballistic missile is the proximity of the tracking system to the launching site. In the past, tracking equipment used in conjunction with missile guidance has not been located in close proximity to the launching site. However, the tactical use of missiles requires that communication to and from the missile take place only near the launching site, and not near the target. Therefore, the present invention utilizes a system which keeps the missile on the correct trajectory (or nearly so) up to and beyond burnout (and prior to peak altitude), and then calculates and controls the trajectory conditions so that a zero-lift trajectory will strike the target. The only apparent disadvantage of this spacing arrangement is the possible increased vulnerability of the launching site to air or missile attack. This disadvantage is offset by the fact that the guidance and launching equipment will be relatively small in size and numbers. In addition this arrangement provides greater flexibility and mobility, and also allows the coordination problems between the guidance center and launcher to be minimized.

Another factor to consider in the guidance of short range missiles is the effect of errors due to variations in drag acting after burnout. Thus, variations in wind velocity, air density, air temperature, etc., considerably reduce the over-all target accuracy. It has been determined that these drag and wind effects occur largely in a relatively short period after burnout. One method of reducing these errors would be to equip the missile with an additional small thrust. This thrust would have to be somewhat greater than the maximum drag in order to insure proper operation of a small rocket motor. The main thrust would be terminated from the ground at a velocity calculated such that the operation of the small thrust from the time of main thrust shutoff to a predetermined later time would result in the missile having the correct position and velocity conditions to cause it to hit very close to the target. A second method of reducing errors due to variations in drag after burnout requires the use of a pitch accelerometer mounted rigidly within the missile. A very accurate measure of the errors which exist at a predetermined time after burnout is made from the ground, and the effects of these errors on the range of the missile are transmitted to the missile and set as an initial condition on a double-integrating pitch accelerometer. During the last twenty seconds of flight, when the flight path is approximately a straight line inclined at an angle of approximately 40° from the vertical, the missile is caused to accelerate in the proper direction and to integrate the preset error to zero. This last operation is done automatically within the missile.

In accordance with another aspect of the invention, the velocity represents a critical parameter of the missile trajectory. It can be shown that when θ (firing angle) is approximately equal to θ_0 (the angle formed by the tangent to the trajectory at impact) that the tangent at the firing point is at a right angle to the tangent to the trajectory at impact. It is clear that position and velocity components parallel to the impact tangent will not affect the impact point, at least to a first-order approximation, whereas the magnitude of the velocity perpendicular to the impact tangent will be very critical in regard to range accuracy. To obtain a high defree of accuracy in the measurement of this critical velocity a combination of Doppler and radar data is used.

Another problem concerned with the missile trajectory is azimuth control. If the missile is launched vertically and then tilted on its trajectory, the initial azimuth accuracy is determined by the gyroscopes and is certainly not adequate. Furthermore, the effects of crosswinds and thrust misalignments will cause the missile to move out of its initial azimuth plane. One solution to this problem is the use of an external radar system. The radar is locked in azimuth, and the error signal is obtained directly as an electrical signal rather than as a mechanical displacement of the antenna. This eliminates noise from the radar servo circuits. It is also possible to use long smoothing times on the azimuth-error measurements so that again the radar accuracy is improved.

One object of this invention is to provide a missile guidance system which results in increased accuracy for ballistic missiles.

Another object of this invention is to locate the tracking system in close proximity to the launching site.

A further object of this invention is to reduce the errors due to variations in drag after burnout.

An additional object of this invention is to obtain a high degree of accuracy in the measurement of the critical velocity at burnout through the use of a combination of Doppler and radar data.

A still further object of this invention is to increase the accuracy of the initial azimuth control by using an external radar system.

The foregoing and other objects of this invention will become more apparent from the following detailed description and from the accompanying drawings, in which:

FIGURE 1 is a schematic block diagram of the guidance control system of the present invention.

FIGURE 2 is a schematic diagram illustrating the range, azimuth and elevation co-ordinates.

FIGURE 3 is an illustration of the missile trajectory showing the points at which various timing and correction functions occur.

FIGURE 4 is a view of the missile showing the principal reference axes intersecting at the missile's center of gravity.

FIGURE 5 is a schematic block diagram of the inertial guidance system and autopilot system used within the missile.

FIGURE 6 shows a block diagram of the autopilot system.

Referring to the drawings, FIGURE 1 shows a block diagram of the guidance and control system designed for use with a ballistic missile 20. The guidance of missile 20 is based on a command guidance system in which the position and velocity of the missile is measured by ground based radio equipment. This equipment comprises a radar tracking system 21, a Doppler radar station 23 and four computers (azimuth and elevation computers 25, postburnout computer 27 and shutoff computer 29. Missile 20 has a radar receiver 22 (which receives command signals from a transmitter in radar system 21), and a beacon 24 which is triggered by these signals and transmits missile position to a radar receiver 28 in radar system 21. Azimuth, elevation, and range-correction commands are transmitted through radar system 21 to the missile to correct significant deviations of the missile from a preset standard trajectory. The guidance system uses a single ground radar Doppler station 23 which transmits a range-correction velocity signal through a postburnout computer 27 and then to the missile by radar system 21. The Doppler system is of the frequency doubling type. It includes ground station 23, located near the launching area, and an airborne transponder 30 in the missile. Ground station 23 contains a crystal-controlled transmitter, a receiver tuned to twice the frequency of the transmitter, which has means for producing a Doppler tone, and a Doppler discriminator for accurately measuring the tone frequency. The missile-borne Doppler transponder unit contains a receiver having an RF amplifier tuned to the ground transmitter, a frequency doubler, and a transmitter in the form of an RF power amplifier to increase the doubled received frequency to a usable power level. The Doppler station working in conjunction with the missile-borne transponder provides an accurate measure of the missile radial velocity. The radial velocity is the line-of-sight vector from the radar Doppler ground station to missile 20. Although this velocity is smaller than the missile velocity by a factor of the cosine of the angle between the line-of-sight vector and the velocity vector, allowance for this difference can be made in the velocity computation. When the free flight trajectory is altered (that is increased in height or slightly flattened) with respect to the minimum velocity trajectory it has the effect of changing the direction of greatest impact point sensitivity of the missile. The line-of-sight between the radar Doppler tracking station and the missile is then colinear with the direction of greatest impact point sensitivity at a desired cut-off point on the trajectory. Radar tracking system 21 working in conjunction with missile-borne radar beacon 24 provides missile position coordinates and velocity components normal to the line-of-sight, both obtained by measuring the azimuth and elevation angular rates. Azimuth and elevation computers 25 and postburnout computer 27 are used to convert position data from tracking system 21 to the required commands to produce the desired target accuracy. Position data from tracking system 21 is also fed to shutoff computer 29. Computer 29 generates a signal of shutoff velocity through radar Doppler station 23 to the missile. After generation of the shutoff velocity signal, the missile velocity decreases to another critical value at which time Doppler station 23 supplies a signal to computer 27 permitting the latter to apply a final range-correction signal to the missile through radar system 21. The elevation computer is quite similar to the azimuth computer except that it programs a given trajectory. It compares the actual position of the missile with the standard position generated as a function of time in the computer. Thus a command is generated which will return the missile to the proper trajectory elevation. Elevation guidance of the missile is terminated at burnout. The actual physical control of the missile is accomplished by movable control surfaces which are actuated by an autopilot system which is more fully described hereinafter.

The radar system utilized in this invention is a modified SCR–584 radar set used in conjunction with a compatible radar beacon incorporating a dual-channel command system. The SCR–584 radar set is described in several articles appearing in "Electronics" magazine and entitled "The SCR–584 Radar" (November 1945, page 104, December 1945, page 104 and February 1946, page 110). The normal SCR–584 radar set provides a tracking accuracy in azimuth of one to two mils. This is not sufficient for use in the present invention which requires an accuracy of a few tenths of a mil. One of the largest sources

of error in this radar set is due to the sticking action and other non-linearities of the azimuth servo. These errors are eliminated by physically locking the azimuth gimbal of the radar antenna so that it always points towards the target. The azimuth electrical error signal, which is normally used to position the antenna, can be used by the azimuth computer to generate the position command. With the radar tracked in elevation an electrical error signal is continuously provided which is proportional to the traverse error angle of the missile from its proper trajectory.

Referring to FIGURE 2 this error angle θ, multiplied by slant range R as measured through the use of a range potentiometer geared to the radar range-tracking system 21, provides an electrical signal proportional to the transverse deviation of the missile from the azimuth guidance plane. This error signal is used in the azimuth computer to generate an azimuth command, which is then transmitted to the missile autopilot through the radar system. These azimuth commands continuously guide missile 20 in the direction of the target. The azimuth computer is designed to provide an optimum compromise between the rapid detection and accurate correction of disturbances causing the missile to deviate from its proper azimuth trajectory, against the inherent background noise or error in the radar traverse angle signal. The term ϕ indicates the elevation angle in the azimuth plane.

It is also possible to use long smoothing times on the azimuth-error measurements so that the radar accuracy is further improved. The ultimate accuracy of the missile will be dependent upon the fraction of the total flight time that is used for azimuth guidance. This guidance period may be continued for some time after burnout subject to the following facts: As the missile travels away from the radar, a given angular inaccuracy corresponds to a larger missile displacement and velocity error by an amount proportional to the range. However, the time to impact is reduced and therefore the effects of the velocity error do not have as long a time to accumulate. Secondly, certain components of the radar noise which limit the accuracy of the radar set increase with range. On the other hand, the higher the vehicle goes, the smaller the disturbing forces (caused primarily by side winds) become, allowing an increase in the smoothing time available and thus an increase in the accuracy of the radar measurements. Also, the higher the point of guidance termination and the smaller the time of flight remaining after guidance termination, the smaller are the errors caused by side winds, time errors, etc., which build up after the cessation of guidance.

Referring to FIGURE 3 an analysis of the range-correction sequence as well as certain parameters for the missile or rocket trajectory will be made. The missile which is a self-propelled liquid propellant rocket, is ignited by conventional means and launched at launching site 31. Both the Doppler radar station 23 and the tracking radar system 21 and associated equipment are located in close proximity to this site. Line 33, which is not drawn to scale, indicates the approximate end of the earth's atmosphere, and shows that a considerable part of the rocket trajectory is in free space. During the initial phase of the trajectory the missile is powered by a rocket motor until point 35 is reached. At this point we have termination of rocket power or the burnout point. If desired an additional small rocket motor may be used on the missile to provide a small amount of additional thrust. This thrust, which would terminate at point 37, would provide a slower ascent rate between points 35 and 37 and thus provide a period in which more accurate position and velocity measurements could be made. The end of the trajectory is indicated by missile impact point 39. The point of greatest concern of the trajectory is at 38 when trajectory conditions are measured for the last time and thus determines final accuracy. The critical component of velocity must be measured as accurately as possible.

The measurement of this critical component of velocity could be accomplished by placing the Doppler station 23 at point X_D where $X_D = -Z \cot \phi_0$ (Z_0 equals altitude of the missile at burnout) and by including a Doppler transponder within the missile.

Although the optimum location of the Doppler station as regards to fuel shutoff is point X_D, the tactical situation requires the Doppler station be located near the launching site. Fortunately the requirements for the range-correction system on the maximum range trajectory also place the Doppler station in close proximity to launching site **31**. Therefore the radar system and the Doppler radar station are located at a convenient point about one thousand feet behind launching site **31**. For other than maximum range trajectories the trajectory can be shaped to achieve this condition. The critical missile velocity is then measured by a combination of Doppler and radar data. Numeral **38** indicates that point on the trajectory which the missile reaches after about 100 seconds of flight. At this point a final range-correction command is sent to the missile. It can be shown from trajectory considerations that the important compnent of velocity as regards impact range errors remains inclined from the horizontal by approximately the angle ϕ_0 for nearly the entire trajectory. A line drawn through the missile at the 100 second point at an angle of ϕ_0 with respect to the horizontal (point **38**) falls nearly through the launching site, thus making this point the optimum location for the Doppler station as regards measurements at point **38**. In fact the Doppler set must be located at this point in order to obtain sufficient accuracy of the critical velocity at point **38**. Numeral **40** indicates that point on the trajectory when the final range correction is initiated. In relation to range guidance the direction of the missile's vector velocity affects the size of the impact point error. The direction giving the greatest impact point error may be called the high impact point sensitivity direction of the missile.

The operations involved in the range-correction sequence of FIGURE 3 will now be analyzed. After the missile has left launching site **31** a shutoff command from computer **29** is transmitted to the missile to shut off the rocket engine (point **35** on the trajectory). Doppler radar station **23** is designed to furnish a tone signal with a frequency proportional to the radial velocity of the missile. A bridge circuit in the Doppler station can be both manually and electrically tuned. Before firing, the bridge is manually tuned to a frequency corresponding to the standard shutoff radial velocity. That is the shutoff radial velocity as calculated from the particular standard trajectory which impacts at the specific target range with the electrical signal at zero. When the Doppler tone frequency coincides with the frequency for which the bridge is tuned, a shutoff signal is generated and transmitted to the missile. As shown in FIGURE 1 shutoff computer receives data from radar system **21** as well as Doppler station **23**. Standard shutoff slant range is preset in the radar station, and an electrical signal is generated in radar system **21** proportional to the deviation of the actual slant range from the standard value. Computer **29** further differentiates the elevation angle data to obtain elevation angular rate, subtracts the standard elevation angle and angular rate values, and linearly sums the range, angle, and angular rate data according to ratios that are functions of the standard trajectory and range. The result is a correction signal voltage fed to Doppler radar station **23** to tune continuously the Doppler bridge. When the Doppler frequency equals the frequency for which the bridge is tuned, the shutoff signal is generated. At point **38** on the trajectory data from the radar and Doppler stations is fed to postburnout computer **27**. This data consists of a range-error correction based on trajectory measurements at point **38** and is computed by calculation of the trajectory range error at impact, assuming a missile flight trajectory without correction. This error, when transmitted to the missile, is stored in a memory device until the missile reaches point **40** on the trajectory. At this point the final correction causes the missile to maneuver towards the target. Postburnout computer **27**, like shutoff computer **29**, is a linear analog unit and is based on the assumption of small deviations of the input quantities from their standard values.

Referring to FIGURE 4 the principal reference axes of the missile are shown intersecting at the center of gravity of the missile. The principal axis extends longitudinally through the center of the missile and constitutes the roll axis **41**. The pitch axis **43** is a lateral line extending through the missile normal to the yaw axis. The normal or yaw axis **45** extends through the missile perpendicular to the pitch axis. Errors in roll, pitch and yaw are, of course, determined in terms of rotation about their respective axes **41**, **43** and **45**.

Referring to FIGURE 5 the inertial guidance system **51** and the autopilot system **53** are shown within missile **20**. The primary function of autopilot **53** is to maintain attitude stability and to effect steering commands as directed by inertial guidance system **51** as well as the ground based guidance equipment. The inertial guidance system follows conventional practice and employs two gyroscopes to serve as error detectors. One has its spin axis vertical and controls the missile in pitch; the other has its spin axis horizontal and controls the missile in both yaw and roll. During the initial burning stage the pitch angle of the missile is caused to follow a preset timed program (designed to accomplish the desired trajectory) by the addition of an appropriate signal to a pitch-gyro pickoff circuit. Yaw and roll signals are taken off the horizontal gyro through error pickoffs on the inner and outer gimbals, respectively. These signals are used to maintain the missile yaw and roll motion as close to zero as possible. In addition to the gyroscopes inertial guidance system **51** uses two accelerometers for controlling the missile flight after fuel shutoff. During the burning period the accelerometers cannot be used because of the effects of thrust and the vibrations from the motor. The signals from these accelerometers, mounted rigidly in the missile so as to measure the pitch and yaw accelerations of the vehicle, become the inputs to pitch and yaw channels in autopilot system **53** after termination of thrust. The missile then tends to become very stable; that is, it orients itself into the relative wind so that it maintains a zero-lift trajectory. The change over from gyroscopic to accelerometer control is accomplished by the fuel shutoff signal received from Doppler radar **23**.

Autopilot system **53** is designed to actuate four control surfaces **55** and attached jet vanes **57** in order to roll stabilize the missile and to yaw and pitch the missile as required.

As shown in FIGURE 6 the autopilot system **53** includes roll signal power amplifying stage **62** which receives roll pickoff signal **61**. In a similar manner pitch and yaw pickoff signals **71** and **81** are fed to the pitch and yaw amplifiers **72** and **82**. The resulting three amplified signals are then fed to a signal mixing circuit **60** in order to place roll signals on all four control surfaces. The output of circuits **60** are fed to signal shaping circuits **70** (or filters) to insure dynamic stability of the missile. Design of the signal-shaping networks is based on the aerodynamic parameters of the missile and the transfer functions of the remainder of the autopilot components. The signals from shaping circuits **70** are sent to four control surface amplifiers **63**, **73**, **83**, **93**, where the signals are built up to the power level required to operate electromechanical transfer valves **65**, **75**, **85**, **95**. These valves control the flow of compressed air to piston-type servo actuators **67**, **77**, **87**, **97** which are mechanically linked to the control surfaces. The actuators are supplied compressed air from the propulsion-system main air tank which continues to supply air to the control system during the entire flight.

Referring again to FIGURE 5 the operational sequence of the command guidance system is shown in relation to missile **20**.

In particular, to guide the missile in azimuth, an azimuth angular position signal is sent out from missile **20**. Radar **21** receives this signal, combines it with range, and sends it to the azimuth computer. The computer compares the actual azimuth-range signal with the standard azimuth-range and the difference, if any, is sent back to radar **21**. Radar **21** sends this difference or correction command to a radar command unit **52** in missile **20**. There a yaw correction signal is sent to autopilot system **53** for correcting the yaw of the missile.

To control the elevation of the missile radar **21** measures the instantaneous elevation of missile **20** and transmits this information to the elevation computer. The elevation computer compares the actual elevation with the standard elevation and the difference, if any, is sent back to radar **21** as a correction command. Radar **21** sends this correction command to radar command unit **52** in missile **20**. Here a pitch correction signal is sent to autopilot system **53** for correcting the pitch of the missile.

To control the shutoff signal to missile **20** a standard shutoff velocity is preset into Doppler station **23** before the missile is launched. During flight the radar station receives range and elevation information from the missile which is sent to the shutoff computer. In the shutoff computer a shutoff velocity correction is determined and applied to the Doppler station to correct the preset shutoff velocity. Missile velocity is measured by Doppler station **23** as received from a Doppler transponder, and when the missile velocity is equal to the corrected preset shutoff velocity, the Doppler station sends a shutoff command **56** to the Doppler transponder to close a propellant valve in the rocket motor.

The final range correction procedure involves two interrelated loops. A final range correction loop to determine the pitch correction necessary to direct the missile more accurately into the target, and a time-to-impact loop to determine the time at which the correction should be sent to the missile. In regard to the final range correction, radar system **21** receives elevation and range information from missile **20**. The range information is compared with a preset range value and the range error, if any, is sent with the elevation information to the range correction or postburnout computer. By comparing this information with preset values, the computer calculates the range correction and stores this value until a timer releases it. Postburnout computer **27** also receives range error and elevation information from radar system **21**. This computer also receives a trigger signal from Doppler station **23** when the instantaneous velocity of the missile is equal to a preset value. Computer **27** compares this information with preset values of velocity and elevation to compute the time-to-impact. When time-to-impact reaches a particular value, the final range correction is

sent to radar **21** which transmits this correction command to the missile. This command is stored in the missile by causing a linear potentiometer to be driven by a constant speed potentiometer for the desired length of time. This range-correction command **54** is fed to inertial system **51** where a final correction signal is sent to autopilot system **53** to maneuver the missile during the last twenty seconds of flight.

It is to be understood that the above described system is illustrative of the principles of the invention. Numerous modifications could be made to this system without departing from the spirit and scope of this invention.

We claim:

1. A control system for guiding a ballistic missile on a predetermined trajectory comprising means for launching said missile at a launching site, radar means located at said launching site for tracking said missile and providing missile position data, Doppler means located at said launching site for measuring the velocity of said missile and providing missile velocity data, azimuth and elevation computer means for receiving and comparing said position data with predetermined standard trajectory data to generate yaw and pitch correction commands respectively, said yaw and pitch correction commands received and transmitted by said radar means to said missile, control means within said missile for receiving and executing said commands to maintain the missile on said predetermined trajectory, a shutoff computer means for receiving and comparing said velocity data with a predetermined shutoff velocity to produce a shutoff command, said shutoff command transmitted to missile by said Doppler means to effect fuel shutoff so that the missile remains on said predetermined trajectory, postburnout computer means for receiving and comparing said position and said velocity data with other predetermined trajectory data to generate a final range correction command, said final range correction command received and transmitted to said missile by said radar means to effect final guidance of said missile.

2. A system as set forth in claim 1 wherein said missile has a plurality of control surfaces to stabilize the missile on its predetermined trajectory, said control means comprising an autopilot system for actuating said control surfaces.

3. A system as set forth in claim 2, including an inertial system, providing missile acceleration data to said autopilot system after said shutoff signal is received by said missile.

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