

QUEST



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Q U A R T E R L Y



**FLYING IN DEEP SPACE:
THE GALILEO MISSION
TO JUPITER (PART TWO)**

**RETHINKING THE
OVERVIEW EFFECT**

**AN INTERVIEW WITH
CHARLES FRIEDLANDER:
FORMER CHIEF
ASTRONAUT SUPPORT OFFICE
CAPE KENNEDY**

**ATLAS VS. A FORD GALAXIE:
GROUND HANDLING
INCIDENTS IN THE
COLD WAR ERA**

**NAVIGATION, GUIDANCE,
AND CONTROL OF A
SATURN ROCKET
AND ITS PREDECESSORS**

Features

- 4 **Atlas vs. a Ford Galaxie:
Ground Handling Incidents in the Cold War Era**
By Joel W. Powell
- 11 **Flying in Deep Space:
The Galileo Mission to Jupiter (Part II)**
By David Clow
- 26 **An Interview with Charles “Chuck” Friedlander
Former Chief of the Astronaut Support Office,
Cape Kennedy**
By Donald Pealer
- 39 **Rethinking the Overview Effect**
By Jordan Bimm
- 48 **Navigation, Guidance, and Control of a
Saturn Rocket and Its Predecessors**
By Ed Durbin

Book Reviews

- 62 **An Acre of Glass: A History and Forecast of
the Telescope**
Book by J. B. Zirker
Review by Gregory A. Good
- 63 **Eyes in the Sky: Eisenhower, the CIA, and
Cold War Aerial Espionage**
Book by Dino Brugioni
Review by James David
- 64 **Pseudoscience Wars: Immanuel
Velikovsky and the Birth of the Modern Fringe**
Book by Michael D. Gordin
Review by Roger D. Launius

Cover Image

Artist's view of *Galileo* flying past Jupiter's volcanic moon Io. The image incorrectly shows the spacecraft's high gain antenna in its fully deployed position. Credit: NASA

FROM THE ARCHIVES



While searching for high-resolution images to accompany the article on “Primate Lives”, volume 20 #4, we came across this undated, uncredited image.

FROM THE ARCHIVES

Gordon Cooper

Normal Apollo crew rotations from back-up crew to prime flight crew was as follows—the back-up crew would be named the prime crew of the third mission down the line in the Apollo flight program. Based on this rotation, I should have been selected as commander of *Apollo 13*. However, office “politics” in the Astronaut Corps, the return to flight status of Alan Shepard after the correction of an inner ear disorder, and the view points of certain NASA managers allowed for the selection of Shepard ahead of me for command of *Apollo 13*. Shepard fell behind in training and was allowed to switch to commander of *Apollo 14*, moving Jim Lovell and his crew

up to *Apollo 13*. Of course, if I had received command of *Apollo 13*, it would have been my “lost moon.” I would not have been able to walk on the moon because of the flaw in the oxygen tank which caused the explosion...If I had been selected for command on *Apollo 13*, there would not have been a falling behind in training because of my extensive work experience during back-up on *Apollo 10*. Shepard was very fortunate to be pulled from command of “13” and placed on “14.” As it turned out, he was the only one of us Mercury guys to actually fly to and land on the moon.

RR Auction, Lot 540,
21 November 2013



NAVIGATION, GUIDANCE, AND CONTROL OF A SATURN ROCKET AND ITS PREDECESSORS (PART I)

By Edgar Durbin

Introduction

This two-part article describes the evolution of systems for navigation, guidance, and control of rockets designed by the group headed by Wernher von Braun. This part covers the V-2 and Redstone rockets.

At the end of World War II, von Braun moved to the United States with about 120 key members of the team that had developed the V-2 rocket in Peenemünde, Germany.¹ This group, which grew to about 4,000 by 1960,² developed the Redstone, Jupiter, Pershing, and Saturn rockets in the United States. Typically R&D vehicles would use some flight-tested components from earlier vehicles, carrying new components as passengers until they had passed flight tests.

Table 1 shows the operational rockets developed by the von Braun group from the V-2 to Saturn. Note the brief time interval between Redstone, Jupiter, and Pershing I. Not shown in Table 1 is HERMES II, an R&D project the group started at Fort Bliss and White Sands. HERMES II was a two-stage, long-range rocket with a V-2 as first stage and a ramjet second stage. The table also excludes space launch vehicles derived from Redstone and Jupiter (Jupiter-C, Juno I, and Juno II). Also omitted from Table 1 is Saturn I, the R&D rock-

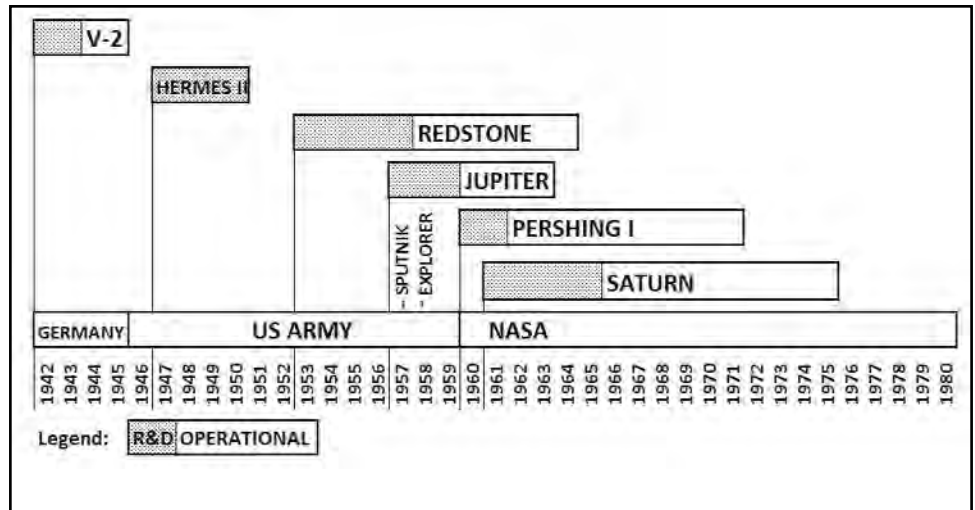


Figure 1. Rocket program chronology, from first R&D flight to retirement. Design study work that preceded R&D launches is not shown. The bottom bar indicates the organizational subordination of the von Braun group. The launches of *Sputnik I* (October 1957) and *Explorer I* (January 1958) are also shown.

et that preceded the operational vehicle Saturn IB. There were 10 launches in the Saturn I program. In Figure 1 the bottom bar shows the organization for which the von Braun group worked. Just as Pershing I made its first R&D flight, the group left military control and became part of a new civilian agency, the National Aeronautics and Space Administration (NASA).

Gyros

All the rockets considered in this

article used gyroscopic devices. Gyros detect changes in direction or velocity and are the sensing devices in inertial guidance systems. A gyro consists of a rotor mounted in a set of gimbals that connects it to the rocket chassis, allowing the rotor spin axis to take any orientation with respect to the rocket.

A gyro is not sensitive to linear accelerations; that is, if it is pushed in any direction through its center of mass it translates. Translation does not change the direction of the rotor spin axis; it just changes the position of the rotor's center of mass. A gyro is sensitive to rotations, however. If it is turned around any direction but the spin axis, it not only rotates around the imposed torque but also around a direction normal to it. This additional rotation is called precession. This behavior is shown in Figure 2 through Figure 5.

A gyro has three mutually perpendicular axes: spin, input and output; see Figure 5. The rotor turns about the spin axis at high speed. When an external force

	V-2 ³	REDSTONE ⁴	JUPITER ⁵	PERSHING I	SATURN IB ⁶	SATURN V ⁷
First operational	1944 ⁸	1958 ⁹	1960 ¹⁰	1962 ¹¹	1966 ¹²	1967 ¹³
Height (ft)	46	69.3	60	34.6 ¹⁴	223.4	363
Diameter (in)	65	70	105	40	274	396
Weight loaded (lbs)	28,440	61,346	108,804	10,275	1,296,000	6,348,659
Max range (mi)	186	200	1,726	345 ¹⁵	-	-
Stages	1	1	1	2	2	3
Fuel	Alcohol and LOX	Alcohol and LOX	RP-1 and LOX	Solid (PBAA) ¹⁶	RP-1 and LOX LH ₂ and LOX	RP-1 and LOX LH ₂ and LOX

Table 1. Operational Rockets Developed by the von Braun group

is applied to the gyro frame, it imposes a torque about the input axis. This causes the gyro to slowly revolve (precess) about the output axis. In mathematical terms, the quantitative vector relation describing this behavior is $T = P \times S$. The input torque T is equal to the cross product of the angular velocity of precession P and the spin angular momentum S .

Any arbitrary torque can be resolved into two components, one parallel to the spin axis, and another perpendicular to the spin axis. The former causes no change in the direction of the spin. The one perpendicular to the spin axis causes the gyro to rotate about the output axis. Thus in analyzing the behavior of a gyro one only needs to consider applied torques that are normal to the spin axis.

V-2

The control system used in most V-2 missiles fired during World War II was the LEV-3. A block diagram of this system appears in Figure 6. Note that it has three parts: a set of three gyros on a mounting plate, a control computer, and the hydraulic devices to move the air rudders and jet vanes. The missile was steered by air rudders on the ends of the four large fins at the base of the V-2 and by graphite jet vanes, which directed the exhaust of the engine. The air rudders were effective only during flight in the atmosphere, and the jet vanes worked only when the engine was operating.

The LEV-3 contained three gyros; see Figure 7. The one mounted vertically at back left is a pendulous integrating gyroscopic accelerometer (PIGA), which controlled cutoff of the fuel and hence the range of the missile. All V-2 missiles lifted off straight up. After four seconds of vertical flight, they began to pitch over in the direction of the target. The pitch maneuver was completed in 40-50 seconds, and the missile then flew at a constant pitch of 47 degrees from vertical until fuel cutoff.¹⁸ All missiles followed this flight plan; they differed only in the length of time they followed this course until cutoff. After cutoff, a missile followed a ballistic (unpowered) trajectory to impact. The two components in the foreground of Figure 7 are the *Horizont* and the *Vertikant*. They were free gyros (without stabilization systems to hold the spin axis stationary in flight)¹⁹

that controlled the missile orientation: the *Horizont* controlled pitch and the *Vertikant* controlled roll and yaw.

Pendulous integrating gyroscopic accelerometer (PIGA)

The left side of Figure 8 is a diagram of the PIGA from a paper by its inventor, Fritz Mueller. The PIGA differed from the *Vertikant* and *Horizont* in having its rotor set off the center line of its supporting frame so that gravity, or another force acting on the frame, would produce a torque on an axis perpendicular to the spin axis of the rotor. The rotor reacts by precessing around a third axis (the direction of flight) normal to the spin axis and the gravitational torque. This precession drives a wheel with contacts for fuel cutoff. The friction of this wheel exerts another torque around the direction of flight. The reaction of the rotor to this torque is to precess about a horizontal axis, causing the rotor to dip, closing the electrical contact at left in Figure 8. This energizes the antifriction motor, creating a torque to which the rotor reacts by precessing back to its original position, breaking the contact. The effect of the switch-motor feedback is to counteract the friction in the contact wheel drive mechanism and to hold the rotor spin axis perpendicular to the direction of flight.

Figure 9 is a sketch of the Mueller Mechanical Integrating Accelerometer carried by the V-2, referred to as Type 1. This figure was supplied by Erich Höhne, one of the Peenemünde veterans who participated in the British Backfire Project in 1945.

A photograph of a Type 1 accelerometer in the collection of the Smithsonian National Air and Space Museum in Washington, DC, is shown in Figure 10. When installed on a V-2 with its cover in place, knobs A and B could be turned by operators, and scale C was visible through a window in the cover. The range of the missile was set by knob B, which rotated gear J and the visible scale C, to which two contacts were attached. Toward the end of flight when the first contact closed, thrust was reduced from 25.7 tons to 8 tons.²³ When the second contact closed, all fuel was cut off and the rocket entered the ballistic phase of its trajectory. This two-stage cutoff was adopted to control the cutoff velocity more precisely. After fuel cutoff, the thrust did not immediately fall to zero,

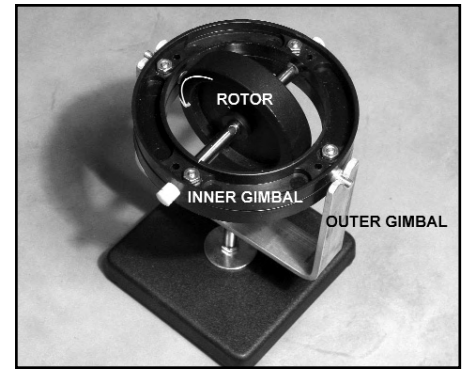


Figure 2. The rotor is spun up in the indicated direction with its axis horizontal.

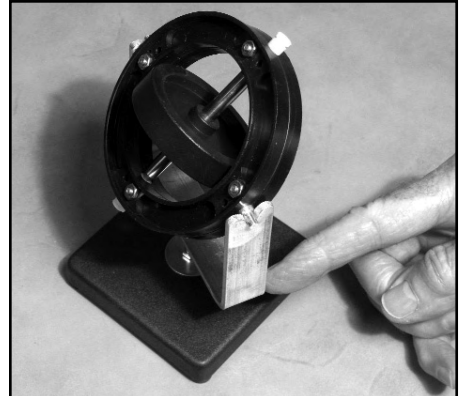


Figure 3. The finger imposes a torque about a vertical axis, and the rotor responds by tilting (precessing) its spin axis downward.

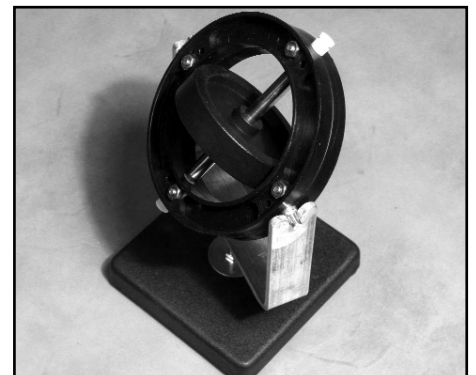


Figure 4. After the torque is removed, the gyro stops precessing and the spin axis continues to point down.

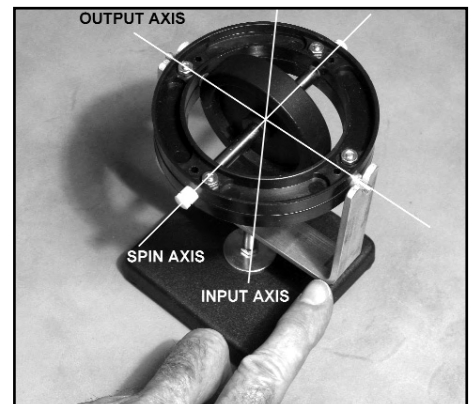


Figure 5. An opposite torque will cause the gyro to precess back up.

but decayed over an appreciable interval. To reduce random variations in this interval, fuel was cut off at a lower thrust. Gear J and scale C were fixed just before launch, and did not move during flight.

Before launch, knob A was adjusted to put gear I and gyro carriage V in their starting positions. A cam attached to the inner face of gear I closed the cutoff contacts carried by scale C.²⁴ Contacts S and T and a mark on top of knob A were used to determine when the starting position was achieved. The solenoid D powered the “caging magnet” of Figure 9. Before launch, this held the gyro spin axis in its starting position, with the spin axis perpendicular to the direction of flight, contacts K in open position, and the antifriction motor off. Without the caging magnet, gravity acting on the gyro before launch would cause it to precess. The angular velocity of the carriage V would be proportional to g , the acceleration due to gravity.

After liftoff the thrust applied by the engines to the frame of the accelerometer caused an additional torque on the gyro. It is important to realize, however, that in flight this accelerometer only measured the acceleration due to thrust minus atmospheric drag. It did not sense gravity after liftoff. If the combination of engine thrust and atmospheric drag was T and the mass of the rocket at liftoff was m , then the total force on the rocket was $T - mg$. By Newton’s Second Law this was equal to ma . The acceleration was $a = T/m - g$. The total torque experienced by the gyro was proportional to $g + a = T/m$. Thus the accelerometer only sensed T , the thrust minus drag, not gravity.

Although the accelerometer only sensed thrust minus drag, the rocket responded to thrust minus drag plus gravity. The output of the accelerometer (the angle through which gear I had rotated since liftoff) was proportional to the velocity of the rocket due to thrust minus drag. There was an additional component of velocity due to gravity. This was calculated for any time after launch and included in the firing tables used to set the cutoff accelerometer before launch. It was not computed onboard the V-2 however. The firing tables for the V-2 assumed a standard thrust, 25.7 tons. If the engines produced a different thrust, the cutoff velocity (due to thrust minus drag) was achieved either earlier or later than standard, and the effect of gravity was more or less than standard, causing the rocket to fall before or beyond the target.

Roll and Yaw Gyro (Vertikant)

The function of the *Vertikant* was to keep the missile from rolling or yawing. The roll axis was vertical at the time of launch. The yaw axis was horizontal at the time of launch and pointed toward the target. The yaw and roll axes defined the flight plane. The pitch axis was perpendicular to the flight plane.

Figure 11 is a sketch of the *Vertikant* (“roll and yaw gyroscope”) and *Horizont* (“pitch gyroscope”), mounted in the nose of the V-2. (This figure was provided by Otto Müller, an engineer and manager at Peenemünde, in a paper he wrote after WWII for

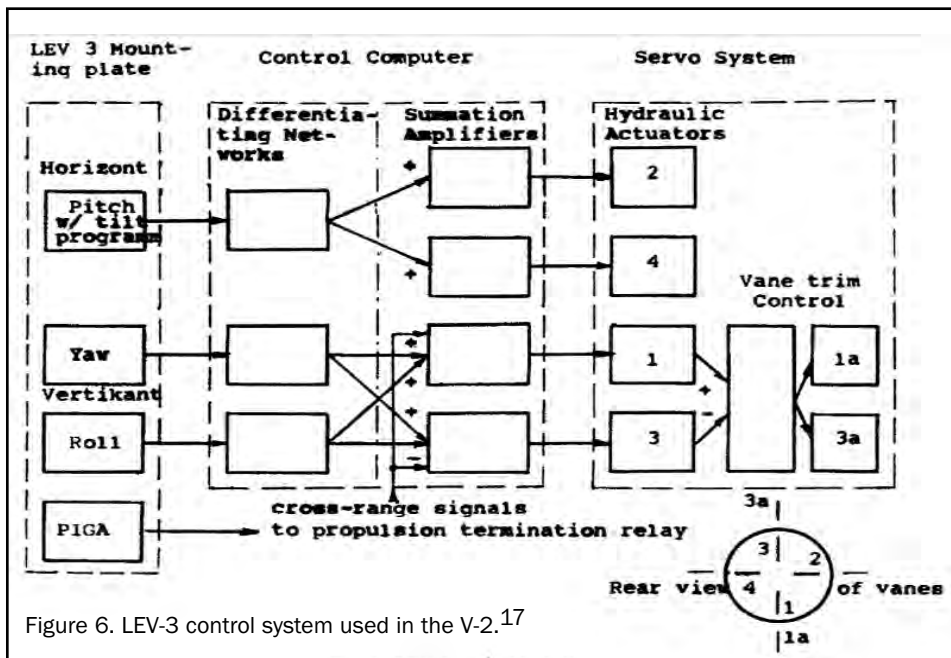


Figure 6. LEV-3 control system used in the V-2.¹⁷

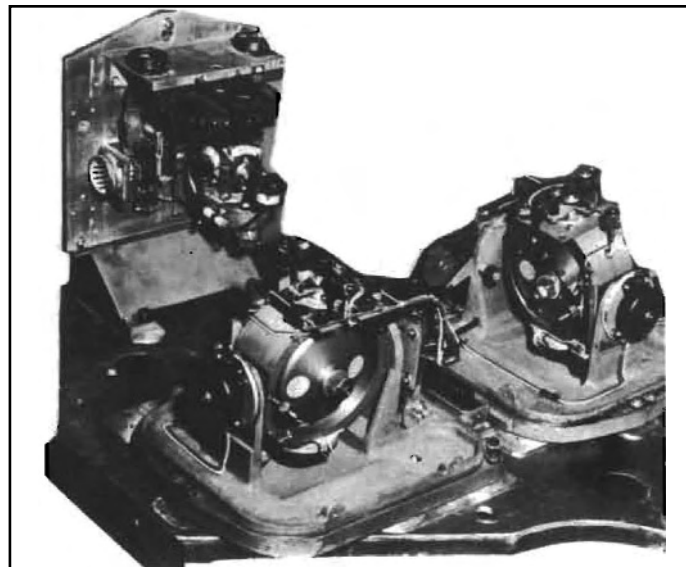


Figure 7. LEV-3 guidance system. The covers over the three gyros have been removed.²⁰

NATO.) The gimbals are indicated schematically by line figures. The vertical dotted line is the roll axis; the line marked “direction of target,” the yaw axis; and the dotted line intersecting them, the pitch axis. The *Vertikant* spin axis was parallel to the pitch axis, making it unresponsive to changes in pitch. However, rotations about the yaw or roll axis would make the gyro precess, which would move the respective contacts (small arrows in the diagram) on the roll and yaw pick-off. The pick-offs were potentiometers. A potentiometer is a coil of resistance wire and a moveable contact (the wiper) that can touch the coil at any point. When a voltage source is connected to the ends of the coil, the voltage at the wiper measures its position on the coil. Hence a potentiometer converted the position of the gyro rotor to a voltage. Voltages from the pick-offs were inputs to the control computer, which sent commands to the jet vanes and air rudders in the tail of the V-2.

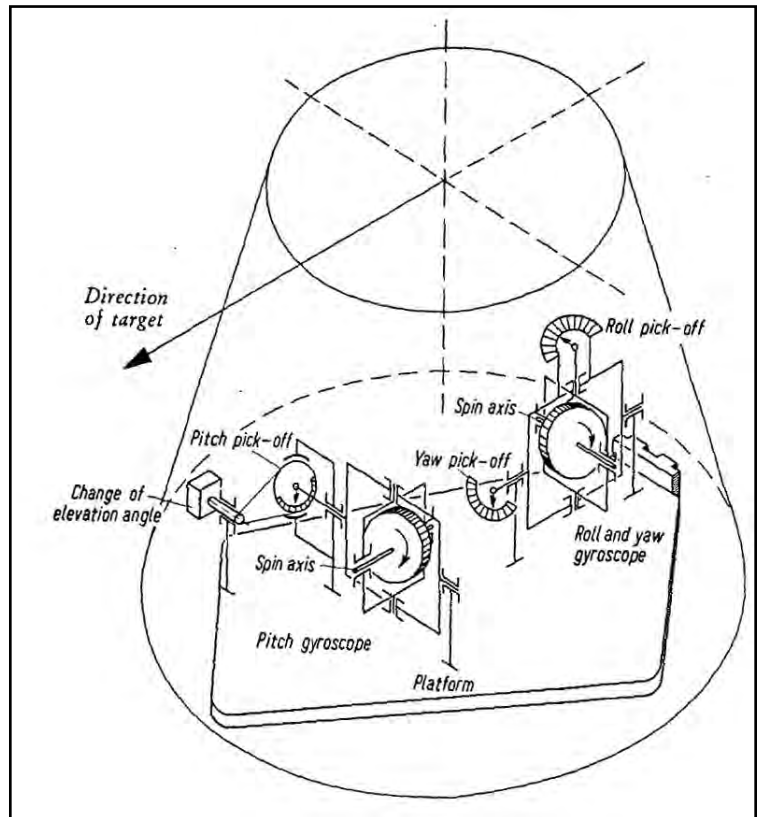
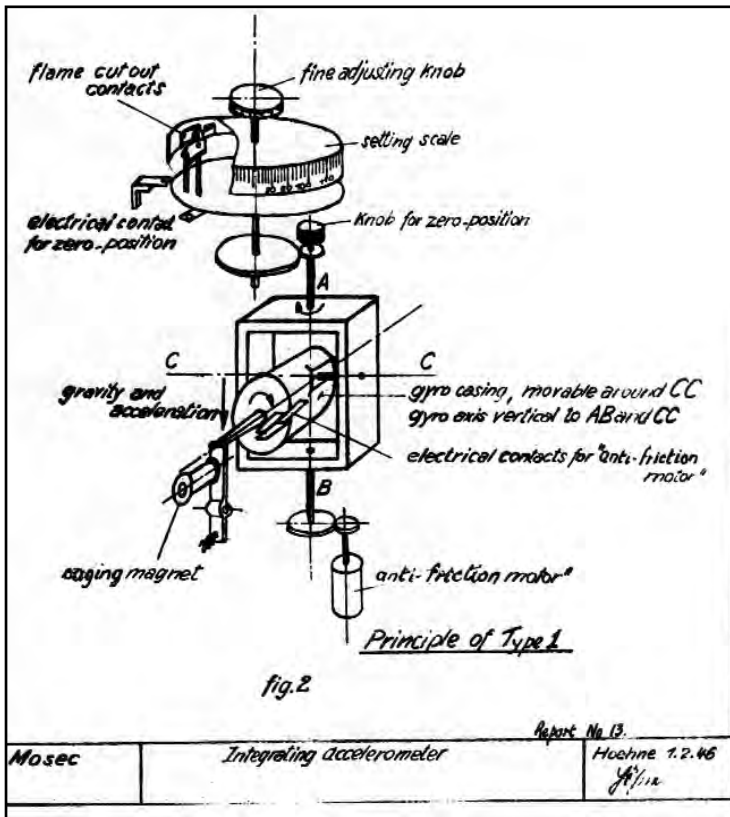
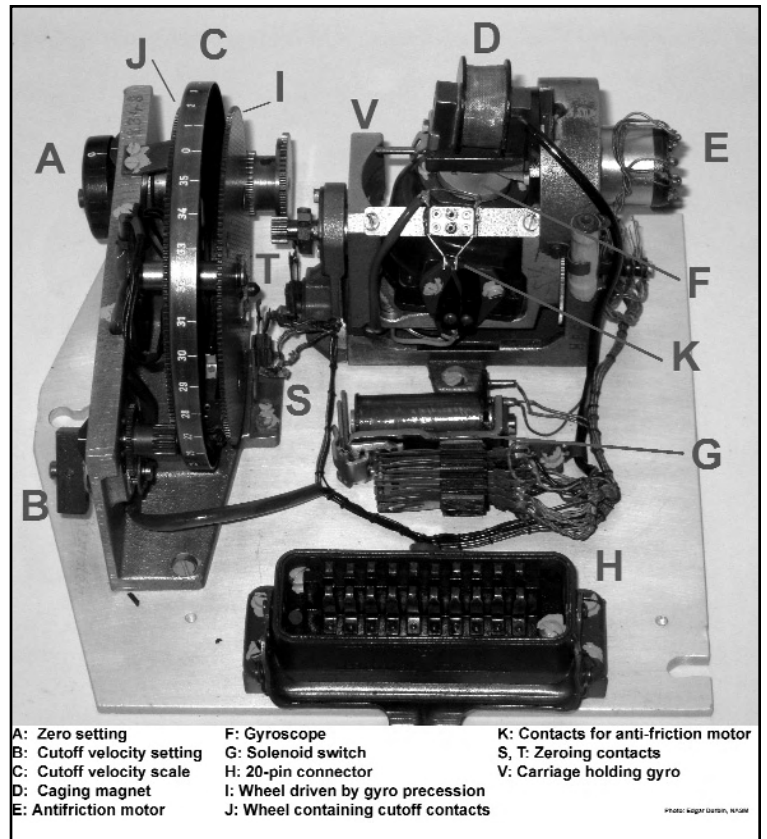
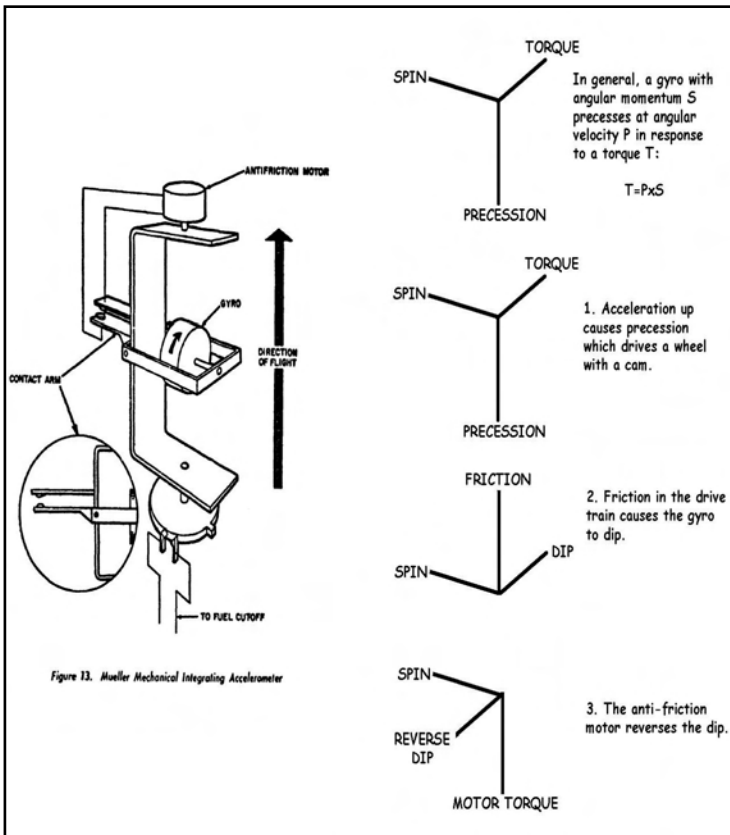


Figure 9. Type 1 Mueller Mechanical Integrating accelerometer carried by the V-2.²²
Credit: Erick Hohne

Figure 11. Sketch of the Vertikant and Horizont gyros.²⁵
Credit: Otto Muller

Figure 12 and Figure 13 show two sides of a *Vertikant*. The rotor is suspended in a gyro frame that allows it to rotate about a vertical axis. This frame is held in a yoke so that it can revolve around a horizontal axis. The gravity switch detected any movement of the gyro frame away from vertical before liftoff, which was counteracted by a stabilizing motor on the yoke, holding the spin axis horizontal. The yaw pickoff detected movement of the spin axis away from the pitch axis, and the stabilizing motor on the bottom of the frame counteracted that movement. This stabilization system was in use while the gyro was being spun up and until liftoff. After liftoff, the gyro was free to precess in response to torques about the roll and yaw axes.²⁶

Pitch Gyro (Horizont)

The *Horizont* controlled the pitch of the V-2. It was similar in construction to the *Vertikant*, with the addition of a device for rotating the pick-off potentiometer that measured the angle between the gyro frame and the yoke attached to the missile. When this potentiometer was rotated, a signal was sent to the control computer, and the missile pitched over until the signal was nulled.

A brass tape attached to the housing of the potentiometer was wound onto a pulley, causing the potentiometer to rotate. The pulley was driven by a ratchet that was advanced 45 times per second by a solenoid. Two timing cams (on the same shaft as the pulley) opened and closed contacts that activated the solenoid.²⁹ See Figure 17.

Control Computer (Mischgerät)

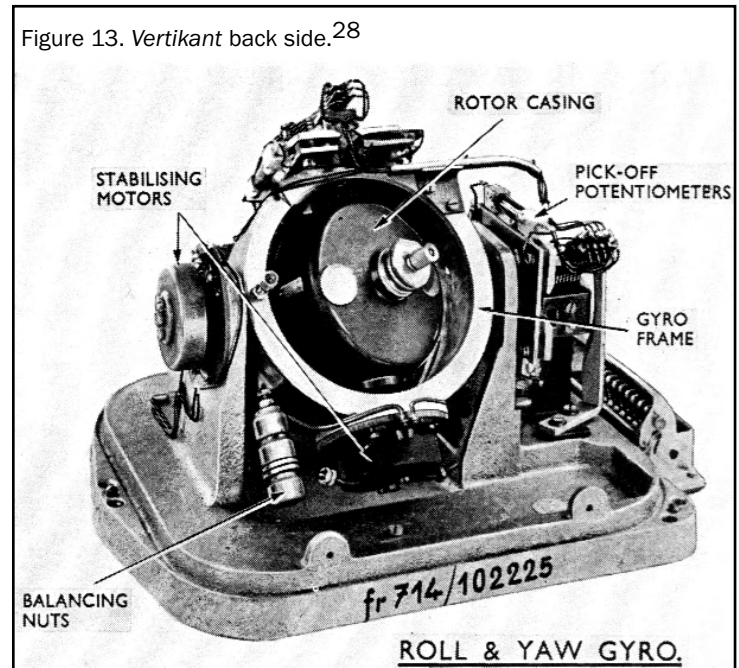
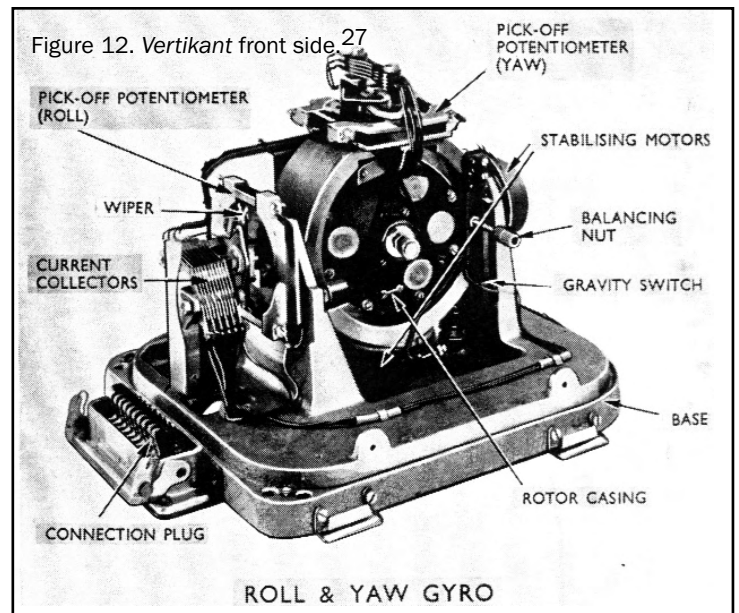
The control computer, or amplifier, was an electronic circuit that converted signals from the *Vertikant* and *Horizont* into commands that were sent to the vane and rudder actuators. See Figure 18. The d.c. voltages from the potentiometers on the gyros were first converted to 500 Hz signals, then passed through differentiating circuits, amplified, and rectified, to produce d.c. commands for the actuators. The differentiating circuits consisted of resistors and capacitors. Helmut Hoelzer, the inventor of the *Mischgerät*, said that these were “RC networks which perform an approximate simple and double differentiation of the gyro output value, good enough to stabilize the system.”³⁴ The amplifiers used four pentode vacuum tubes and a d.c. power supply used a diode vacuum tube.³⁵

Time or Sequence Switch

Although not included in the block diagram of the control system (Figure 6), the time or sequence switch controlled some actions of that system. It turned on the tilt program motor, and commanded fuel cutoff after 65 seconds if the cutoff gyro had not already do so. Other functions of the sequence switch were to pressurize the LOX tank and to arm the warhead. An electric motor rotated a shaft holding 18 cams, which opened and closed 18 switches.³⁷ An example of the earlier of two models of the sequence timer appears in Figure 19.

Additional Developments

Several components were developed during the R&D phase of the V-2 program that saw limited or no operational use.



	V-2 ⁴⁵	Redstone ⁴⁶
Fuel	Alcohol-water and LOX	Alcohol-water and LOX
Range (miles)	186	200
Height (feet)	46.1	69.3
Diameter (inches)	65	70
Warhead Weight (pounds)	2,204	6,305
Launch Weight (pounds)	28,000	61,207
Thrust (pounds)	56,700	78,000
Control	LEV-3 autopilot	ST-80 stabilized platform
Number Built (operational)	5,950 ⁴⁷	85 ⁴⁸
Operational Date	1944	1956

Table 2. V-2 and Redstone comparison

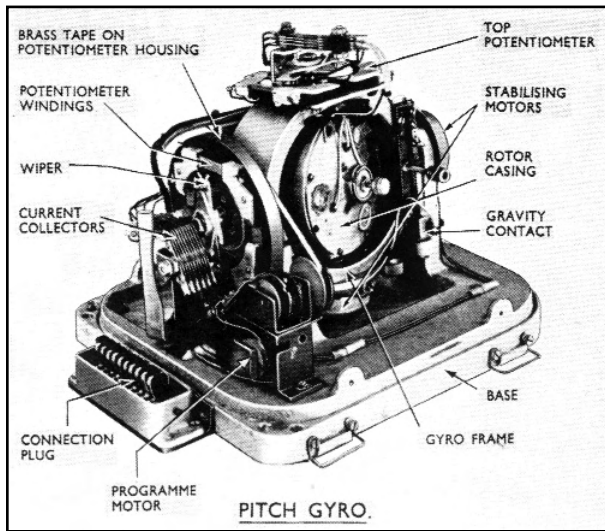


Figure 14. *Horizont front side.* ³⁰

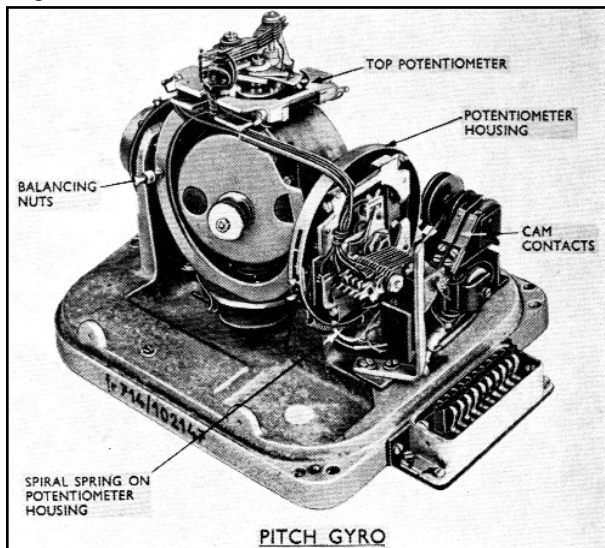


Figure 15. *Horizont back side.* ³¹

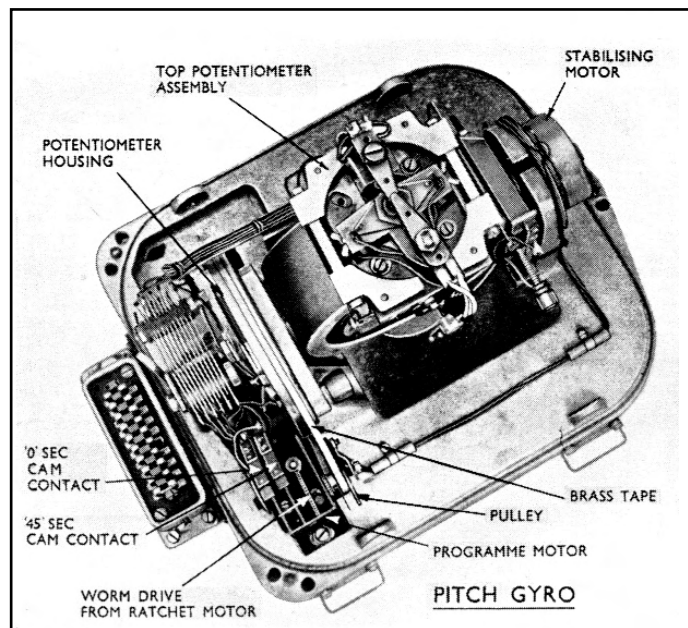


Figure 16. *Horizont top side.* ³²

An electrolytic integrating accelerometer for fuel cutoff was built by Buchhold and Wagner that could take the place of the mechanical device developed by Mueller shown in Figure 8, Figure 9, and Figure 10.³⁹ Another accelerometer invented by Schlitt was similar to a loudspeaker coil and magnet. It measured lateral accelerations on some R&D flights.⁴⁰ Stabilized platforms were built by the company Kreislergeräte GmbH (Gyro Devices, Ltd.) for the A-3, the A-4 (aka V-2), and the A-5. The SG-66 stabilized platform (Figure 20) was tested on the A-4 but was not used in the operational missile.⁴¹

Redstone

The development of the Redstone missile began in 1950, after the von Braun group had moved from Fort Bliss, Texas to Redstone Arsenal in Huntsville, Alabama.⁴³ The new missile had many similarities to the V-2; see Table 2. Both missiles burned an alcohol-water mixture. Both missiles flew preplanned trajectories. The missiles were aligned vertically at launch, with fin #1 pointing toward the target azimuth.⁴⁴ Steering was accomplished by air rudders (effective in the atmosphere) and by jet vanes (effective until engine cutoff).

Flight Phases

Unlike the V-2, the warhead of Redstone separated from the rocket engine. The entire Redstone missile participated in Phase I, which began at launch and ended at engine cutoff. Phase I lasted from 96 to 107 seconds, depending on the target range. Phase II extended from cutoff to the separation of the thrust unit from the missile body (see Figure 21). Separation occurred 127 seconds after launch. Phase III lasted from separation until the start of re-entry into the atmosphere. Phase IV began at re-entry and ended on impact. During Phase IV the guidance unit directed motion of the four fins at the base of the missile body to control its attitude and to guide it on the intended (standard) trajectory. The standard trajectory was the path from launch to target that would be followed if all the standard conditions (for example, thrust, aerodynamic misalignment, wind, gravity, gyro drift) occurred during the actual flight.

	Phase I	Phase II	Phase III	Phase IV
Definition	Launch to cutoff	Cutoff to separation	Separation to re-entry	Re-entry to impact
Lateral guidance	Active			Active
Range guidance	Compute cutoff			Active
Attitude control	Active	Active	Active	Active

Table 3. Guidance and control in Redstone flight phases

During Phase I, control was performed both by the air rudders at the base of the thrust unit and by jet vanes extending into the exhaust of the engine. Guidance was active during Phase I to hold the missile on the standard trajectory. During Phases II and III the missile was unguided, though the guidance system measured and stored deviations from the standard trajectory. The attitude of the missile body was controlled by a set of air jets next to the fins on the missile body. At the start of Phase IV deviations from the standard trajectory were corrected by commands to the fins, and guidance and control continued until impact.⁴⁹

Coordinate System

Navigation requires a coordinate system by which to specify vehicle position, velocity, and attitude. Frequently this is a set of three axes that intersect at an origin and are mutually orthogonal. For example, the origin may be a zero milepost in the capital city, and the three axes may be the north-south axis, the east-west axis, and the vertical at the zero milepost. The Redstone coordinate system origin was at the launch site. Two axes were in the plane of the missile's trajectory: the slant range and the slant altitude. The slant altitude axis was parallel to the tangent to the trajectory at the point of impact. In Figure 22 this axis is labeled "impact coordinate." The slant range axis was the perpendicular line from the launch point to this tangent. In Figure 22 this axis is labeled "range coordinate." The slant range axis was tilted up at an angle epsilon from the horizontal. The third coordinate was the cross range or lateral coordinate. It was perpendicular to the flight plane. One goal of Redstone guidance was to keep the cross range zero. This choice of coordinates simplified guidance equations.⁵²

Guidance and Control System

The Redstone guidance and control system (Figure 23) differed in several ways from the LEV-3 carried by the V-2 (Figure 6). Redstone carried a stabilized platform. Though the German company Kreislergeräte had developed the SG-66⁵³ stabilized platform (stabipla) for the V-2 missile, the operational V-2 flew with the simpler, cheaper, lighter LEV-3 control system was made by Siemens. Improvements in gyros and gimbal systems made after World War II in the United States, plus the increased range and accuracy requirements of the Redstone, led to use of a stabilized platform in the new missile. Whereas the V-2 had two control gyros and one cutoff accelerometer, all fixed to the missile body, the Redstone had

three stabilizing gyros to hold the stabilized platform in a fixed attitude and two accelerometers, all on the stabilized platform. In place of the single control computer (*Mischgerät*) on the V-2, the Redstone had two guidance computers (lateral and range) and a control computer. The timer sequence switch used on the V-2 was replaced on Redstone by a three-track 16-mm tape recorder called the program device. Track 1 sent pulses that caused the pitch potentiometer to rotate, sending a signal to the control computer that caused the missile to change its pitch.⁵⁴

Stabilized Platform

Figure 24 shows the ST-80 stabilized platform carried by Redstone installed in the missile instrument compartment. An ST-80 without a cover appears in Figure 25. The two larger cylindrical objects are stabilizing gyros, and the two smaller cylinders are accelerometers, as seen from Figure 26. Figure 27 shows how the ST-80 was oriented in the Redstone.

The purpose of a stabilized platform was to enable measurement of accelerations and vehicle attitude in a coordinate system that had fixed orientation in inertial space; that is, the coordinate system translated and accelerated but it did not rotate. The accelerometers were mounted within a set of gimbals connected to the rocket. (Such gimbals are seen in Figure 2 connecting the rotor to the table.) To sense any rotations, three stabilizing gyros were mounted with the accelerometers. Signals from these gyros were sent through feedback networks to motors mounted on the gimbal bearings to counter the rotations, thus holding the platform in a constant attitude.

Two sets of measurements were made on the stabilized platform: position and attitude. Position was obtained from the accelerometers, which sensed translation along the axes of the platform coordinate system. Attitude (the roll, pitch, and yaw of the vehicle) was given by the angles of the gimbal bearings.

The gimbals used in the ST-80 were called "internal." The accelerometers and stabilizing gyros were mounted on a stabilized ring, and the gimbals connecting this to the rocket were inside the ring. See Figure 28. In contrast, a set of external gimbals surrounds the accelerometers and stabilizing gyros. See Figure 29. The advantage of internal gimbals was that they were lighter than external gimbals. Internal gimbals had ample range of motion about the pitch axis but limited range of motion about roll and yaw axes. This was satisfactory for ballistic missiles, but Saturn had to roll after launch through larger angles to reach its flight azimuth. The ST-124 carried by Saturn therefore used "external" gimbals, as shown in Figure 29. The SG-66 developed for the V-2 also had external gimbals.

The ST-80 carried two accelerometers, to measure accelerations along the slant range and cross range.⁶¹ The value of epsilon depended on the range to the target, varying from 20 degrees for nearby targets to 43 degrees for the most distant targets.⁶² Epsilon was set to the value appropriate for the target during prelaunch alignment by rotating the slant range accelerometer.

The designers of the Redstone decided to avoid the use of vacuum tubes, to increase reliability.⁶³ The V-2 had used vacuum tubes in its control computer.⁶⁴ At first, magnetic amplifiers were used instead of vacuum tubes, but transistors were introduced later in the input stages of amplifiers, reducing their power, weight, and

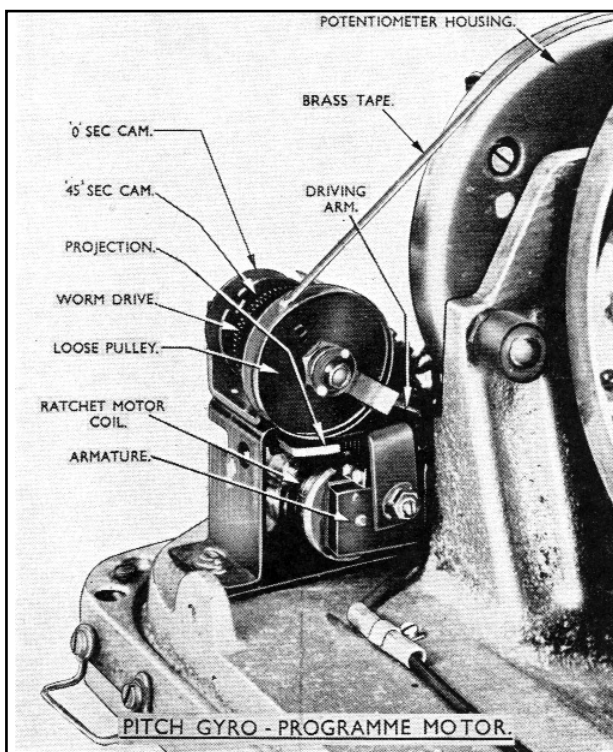


Figure 17. Mechanism on pitch gyro to control the pitch program.³³

space. Servo amplifiers for the accelerometers and stabilizing gyros were transistorized, replacing magnetic amplifiers with a reduction in space and weight but no loss in reliability.⁶⁵ The control computer used magnetic amplifiers.⁶⁶

Servo Systems

Stabilization circuits, such as those described above to counter friction in the V-2 PIGA, were known by the time of Redstone as examples of servo systems. They consisted of a sensor, an electronic circuit to process the signal from the sensor, and an electromechanical device (a motor) to counter the motion detected by the sensor. Such circuits embodied “negative feedback.” The V-2 PIGA was called a “bang-bang” circuit, because the contact banged from one side to the other of the contacts, turning the anti-friction motor on or off in one direction or the other. The AB-5 accelerometers carried by Redstone had continuous position sensors so that the servo motors could provide continuously variable forces to cancel friction. In addition to two servo circuits for the two accelerometers, Redstone carried three servo circuits in which the three stabilizing gyros were the sensors to stabilize the ring on which the accelerometers were mounted; and two servo circuits in which pendulums were the sensors to stabilize the ring during platform alignment before launch.⁶⁷

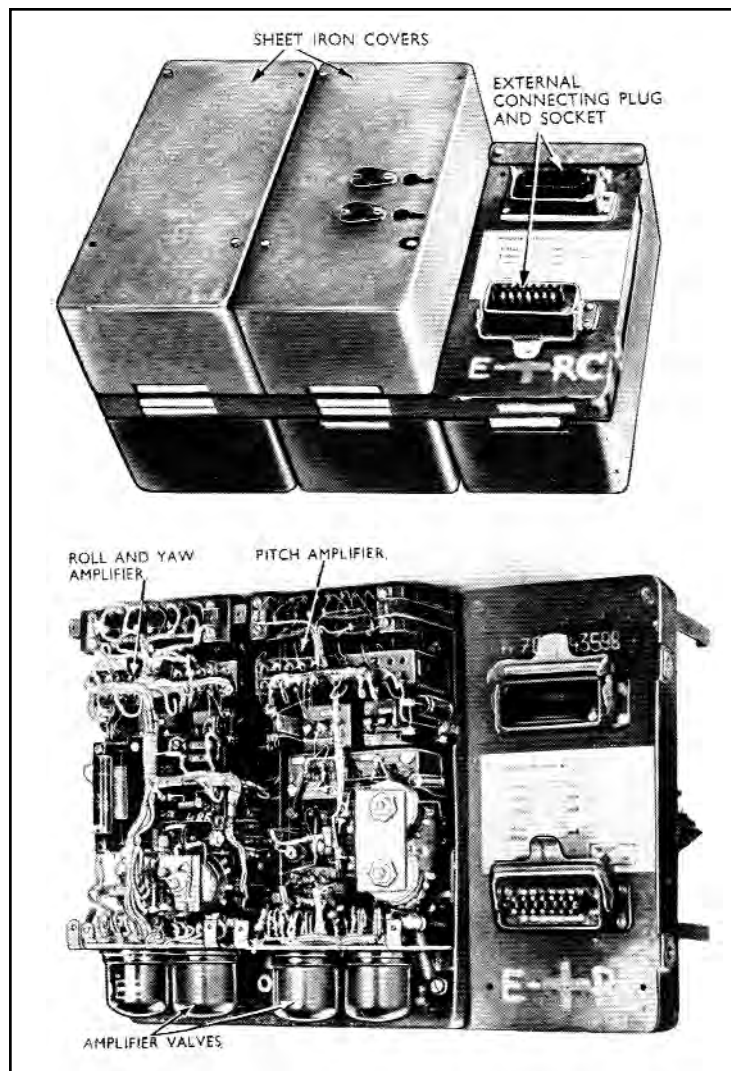


Figure 18. V-2 control computer (*Mischgerät*), covered and uncovered.³⁶

Guidance Computers

The Redstone lateral and range computers were ball and disk integrators, as shown in Figure 30. The rotor of the gyro accelerometer precessed at a rate proportional to the acceleration. The total angle precessed was proportional to the integral of acceleration over time, or velocity. The synchro transmitted this rotational motion to the gears at the input to the guidance computer, causing the wiper on the velocity potentiometer to move. (A synchro is a pair of rotary transformers whose windings are connected so that movement of the synchro transmitter causes the rotor of the synchro receiver to move to the same angular position. It is the means by which mechanical motion can be transmitted over electrical wires.) The output of this potentiometer was thus proportional to the total angle precessed and to total achieved

velocity.

In the right half of the guidance computer, a motor rotated a horizontal disk at a constant speed. This motion was transmitted by balls to a roller, which moved the wiper of a second potentiometer. The speed of the wiper depended on the distance of the balls from the center of the disk, and this was varied by the lead screw. This distance was proportional to velocity. The position of the wiper on the second potentiometer was thus proportional to the integral of velocity over time, which is displacement.

On the right sides of the velocity and displacement potentiometers are other wipers. The positions of these wipers determined the velocity and displacement at cutoff. The settings of these wipers were

obtained from firing tables. For a given range, these tables would provide the nominal slant range and slant range velocity at cutoff. During flight the wipers on the left sides of the potentiometers would move toward the right side wipers, so the potentiometer outputs would diminish toward zero. The actual moment of cutoff was determined by calculating in the control computer a function of the two potentiometer voltages.

Gas Bearings

Gas bearings were used in the stabilizing gyros, the gyro accelerometers, and in the pendulums that sensed vertical before launch for stabilized platform alignment. Gas bearings reduced the drift of these instruments and increased the accu-

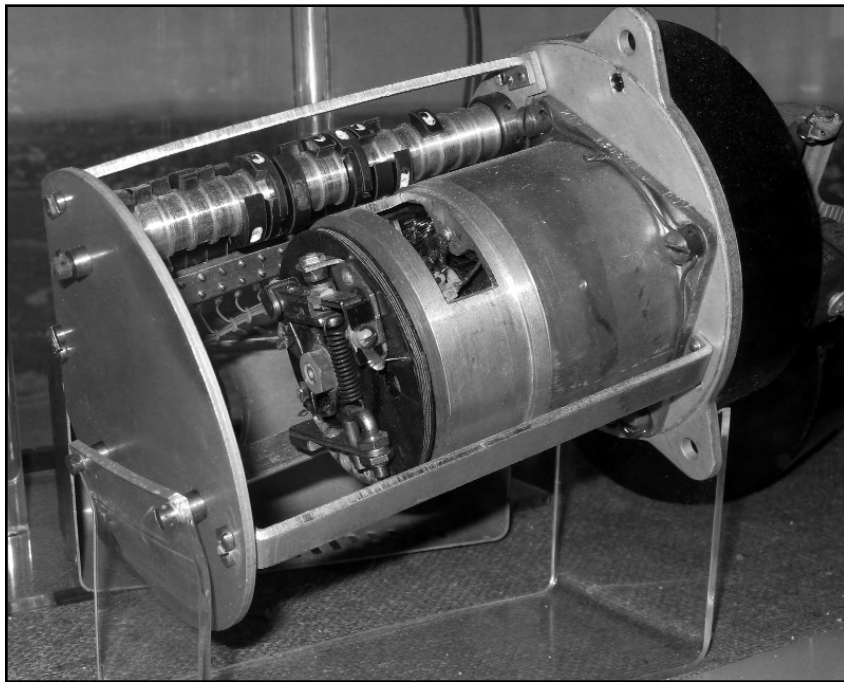


Figure 19. V-2 sequence timer at the New Mexico Museum of Space History in Alamogordo.³⁸ Credit: Edgar Durbin

racy of Redstone missiles, compared to a missile guided by gyros with ball bearings. Note that ball bearings continued in use on the spin axis and on the input axis; gas bearings were used only on the precession axis.

Figure 31 shows a disassembled gyro with a gas bearing. The rotor and its motor are housed in a beryllium cylinder, which is contained in an outer cylinder. The gap between the two cylinders is 15-20 microns.⁶⁹ The flow of gas supports the inner cylinder with negligible friction. Figure 31 does not show the motor, the power connections to the motor, or the pickoff sensor that detects rotation of the inner cylinder.

Use of LEV-3 on Redstone

While the operational Redstone ballistic missile used the ST-80 stabilized platform, some Redstone R&D vehicles carried the LEV-3.⁷⁰ Even after development of the Redstone ballistic missile had completed, the LEV-3 guided Redstone versions used in other projects. To allow a heavier payload, the lighter LEV-3 was used in place of the ST-80 in the Jupiter-C.⁷¹ Despite its name, the Jupiter-C was not a variant of the later and much larger

Jupiter ballistic missile, but was a Redstone with added upper stages.⁷² The LEV-3 guided the launch of *Explorer I*, the first US satellite, and eight other Jupiter-C launches 1956-58. The LEV-3 was also used in six Redstone-Mercury vehicles 1960-61 including two that launched astronauts in one-man Mercury capsules on sub-orbital flights.⁷³ This version of the LEV-3 had an air bearing in the pitch gyro.⁷⁴ The supply of wartime German-made LEV-3s was insufficient so Waste King Corporation manufactured new LEV-3s in the United States.⁷⁵

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About the Author

Edgar Durbin has worked part-time at the Smithsonian Institution National Air and Space Museum, Department of Space History, since retiring from government service in 2002. Most of his research there has been on the navigation, control, and guidance of rockets. He received a bachelor of arts degree in mathematics from Harvard University in 1962, a bachelor of arts degree in physics from Oxford University in 1964, a doctorate in physics from Rice University in 1972, and master's

degree in public administration from the Kennedy School of Government at Harvard in 1977.

Notes

1. *Rocket Science: A Historic Context and Assessment of U.S. Army Cold War Properties 1946-1989*. Redstone Arsenal, Alabama. Historic Resource Assessments, Fort Worth, Texas [November 2000], 16. Michael J. Neufeld. *Von Braun, Dreamer of Space Engineer of War*, 216; "By one count, Ordnance brought over 127 German rocketeers in the first wave, but not all of them were ever in the West at the same time."
2. Roger E. Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915-1990*, NASA [1989]. "[O]n 15 March 1960 ABMA's 4000-person Development Operations Division, headed by Wernher von Braun, was transferred to NASA along with the big Saturn booster project."
3. Gregory P. Kennedy, *Vengeance Weapon 2: The V-2 Guided Missile*, National Air and Space Museum, Smithsonian Institution Press [1983], 84.
4. John W. Bullard, *History of the Redstone Missile System*, US Army Missile Command; [15 October 1965], 100.
5. James M. Grimwood and Frances Strowd, *History of the Jupiter Missile System*. U.S. Army Ordnance Missile Command [27 July 1962], 148.
6. *Skylab Saturn IB Flight Manual*, NASA MSFC [30 September 1972]. MSFC-MAN-206, iv, 1-5.
7. *Saturn V Flight Manual SA-507*, NASA MSFC [15 August 1969, changed 5 October 1969], MSFC-MAN-507, 1-6.
8. *Vengeance Weapon 2*, 38.

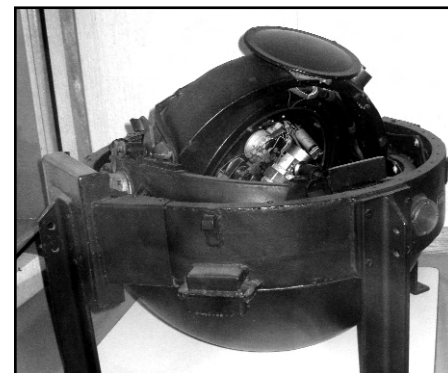


Figure 20. SG-66 belonging to NASM on display at the New Mexico Museum of Space History in Alamogordo.⁴²

Credit: Edgar Durbin

9. *History of the Redstone*, 121-123.
10. *History of the Jupiter*, 103.
11. Elizabeth C. Jolliff, *History of the Pershing Weapon System*, US Army Missile Command, Redstone Arsenal, AL [20 May 1974], 117.
12. First Saturn IB launch, SA-201, was on 26 February 1966.
13. First Saturn V launch, SA-501, was 4 November 1967.
14. *History of the Pershing*, 49.
15. *History of the Pershing*, 49. Maximum optimum range was 345 miles. *History of the Pershing*, "Maximum range, which had

- been the major point of contention in establishing the program, was not prescribed."
16. *History of the Pershing*, 48.
17. Walter Haeussermann, "Developments in the Field of Automatic Guidance and Control of Rockets," *AIAA Journal of Guidance and Control*, May-June 1981, Vol. 4, No.3, 225-239. AIAA 81-4120. Figure 4, 227. Reprinted with permission of the American Institute of Aeronautics and Astronautics.
18. "Report on Operation BACKFIRE." The War Office [UK], London, S.W. 1, [January 1946], Volume 2, 138; Volume 4, 77. "Ministry of Supply Establishment Cuxhaven

- ("MOSEC") Technical Reports." Ministry of Supply Establishment Cuxhaven [UK]. GP/WORK/5/A45. Report 1. *Vengeance Weapon 2*, 70.
19. Earl Finkle, "Workhorse of Inertial Guidance: A Consumer-goods Company Produces Low-cost Guidance Systems," *Missiles and Rockets*, [February 1958], 92. Fritz K. Mueller; "A History of Inertial Guidance", U.S. Army Ballistic Missile Agency, Redstone Arsenal, AL. DTIC AD419538, 7. Republished in *Journal of the British Interplanetary Society*, Vol. 38, [1985], 180-192. A free gyro is one without constraints to precession; i.e. one without a feedback mechanism to hold the spin axis

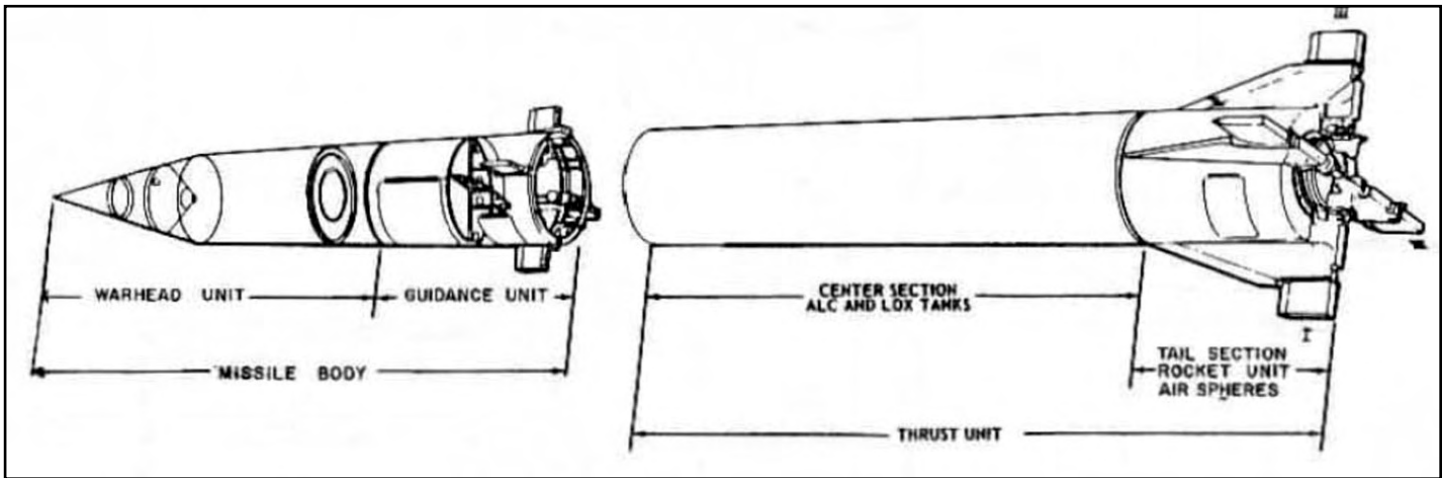


Figure 21. Redstone stages.⁵⁰

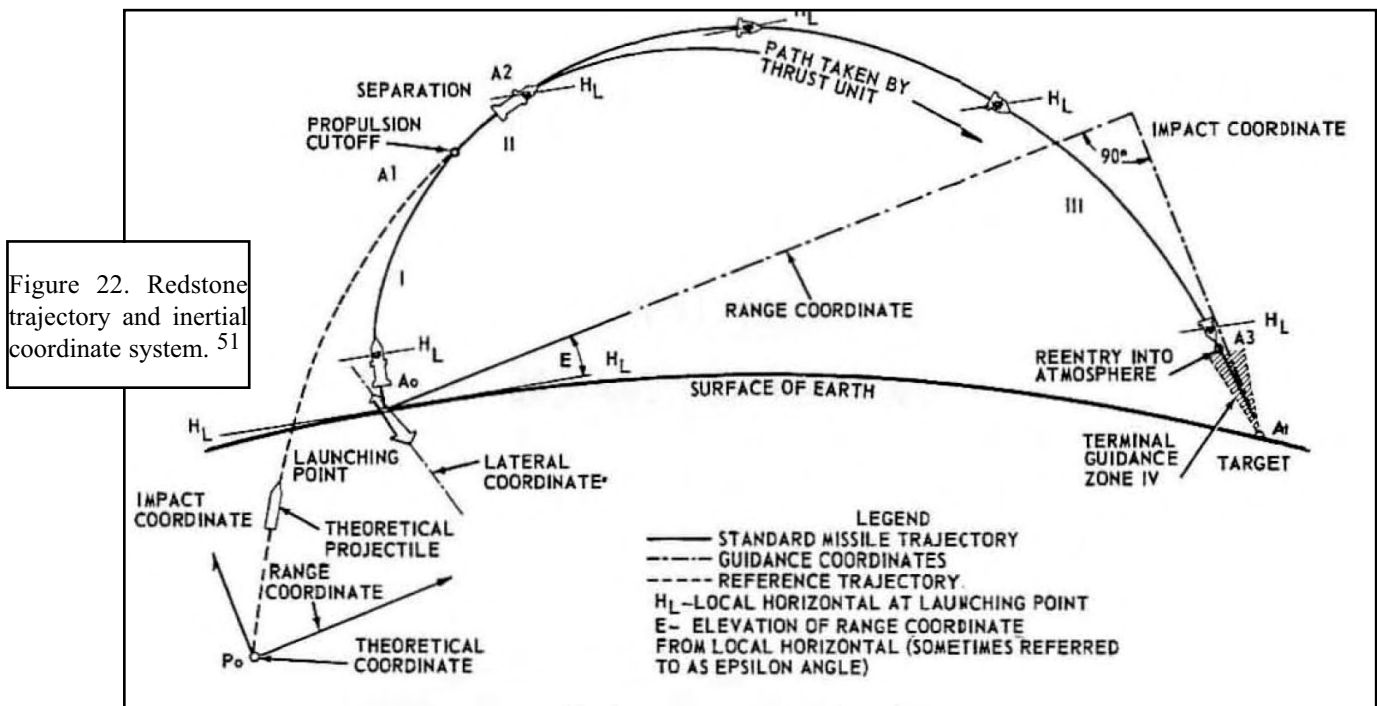


Figure 22. Redstone trajectory and inertial coordinate system.⁵¹

pointing in a fixed direction. Roger E. Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles*, NASA History Office SP-4206, [1996], 243. <http://history.nasa.gov/SP-4206/sp4206.htm> James S. Farrior, "Inertial Guidance, Its Evolution and Future Potential," Chapter 9, *Aeronautical Engineering and Science From Peenemunde to Planetary Space. Honoring the Fiftieth Birthday of Wernher von Braun*. McGraw-Hill, [1963], 152.

20. Fritz K. Mueller, "A History of Inertial Guidance," *Journal of the British Interplanetary Society*, Vol. 38 [1985], 180-192. Also published in Michael Neufeld, *The Rocket and the Reich*, preceding page 83 where it is cited "SI neg. no. 86-1067".

21. Mueller, *A History of Inertial Guidance*, 19. Explanation on the right by the author.

22. MOSEC Report 13 Figure 2. NASM Library Technology Files, V-2.

23. *Vengeance Weapon 2*, 71.

24. MOSEC Paper 13, 2. "The rotation around the axis AB is transmitted by gearing to a disc, which moves concentrically with another plate carrying two adjustable electrical contacts. When, during flight, the rota-

tion round the axis AB reaches a value equivalent to the velocity required for flame cut-off, the two pairs of electrical contacts will be closed in turn by a cam on the driven disc, and will transmit the preliminary, and main control signals for the flame cut-off, the preliminary control signal to reduce the thrust to 8 tons, being given when the velocity is 95% of the final requirement."

25. Otto Müller, "The Control System of the V-2," NATO AGARD First Guided Missiles Seminar, Munich, Germany, April 1956, 84.

26. MOSEC Paper 10, 2. "Before launching the gyros have to be adjusted so that the axes of angular momentum have the desired position. This is done electrically by torque producing magnets." *Backfire*, Volume 2, 136. "When running up to speed, the inner precision axis is maintained vertical by a stabilizing motor under the mounting for the motor housing, controlled by a gravity switch on the side of the mounting...A similar stabilizing motor is fitted to the end of the gyro to counteract any tendency of the torque axis to move from a position at right-angles to the middle precision axis."

27. *Backfire*, Volume 2, 136. Figure 96.

28. *Backfire*, Volume 2, 136. Figure 97.

29. *Backfire*, Volume 2, 136-138.

30. *Backfire*, Volume 2, 137. Figure 98.

31. *Backfire*, Volume 2, 137. Figure 99.

32. *Backfire*, Volume 2, 137. Figure 100.

33. *Backfire*, Volume 2, 138. Figure 101.

34. Hoelzer, Helmut. "Guidance and Control Symposium" in *The Eagle Has Returned*, 301-317. American Astronautical Society, Alamogordo, NM, 5-9 October 1976, Figure 12, 314) and Haeussermann (5-81, Figure 8, 229) show an RC circuit that is slightly different than that shown in the detailed *Mischgerät* circuit diagram in *Backfire* Volume 2, Plate 65.

35. *Backfire*, Volume 2, 65.

36. *Backfire*, Volume 2, 141.

37. *Backfire*, Volume 2, paragraphs 182-184.

38. Photograph by the author. See page 53.

39. Thomas M. Moore, "German Missile Accelerometers," *Electrical Engineering*, Vol. 68, No. 11, 996-999. Thomas M Moore, "V-2 Range Control Technique," *Electrical Engineering*, July 1946, 303-305. MOSEC Report 14. *Vengeance Weapons 2*, 71.

40. Mueller history, 18. German Missile Accelerometers, 999. Haeussermann 5-81, 229. Helmut Hoelzer, "Oral history of Helmut Hoelzer, recorded 10 November 1989 at Huntsville, Alabama by Michael Neufeld," National Air and Space Museum, 11, 48, MOSEC Report 17.

41. Mueller history, 4-7.

42. Photograph by the author. See page 52.

43. *Redstone History*, 22: "On 10 July 1950 the Office, Chief of Ordnance directed the Ordnance Guided Missile Center to conduct a preliminary study of the technical requirements and possibilities of developing a 500-mile tactical missile that would be used principally in providing support for the operations of the Army Field Forces."

44. For the V-2, John A. and Ted A. Woerner, translators. "A4 Fibel." US Army Ballistic Missile Agency Redstone Arsenal, Alabama, [1957], 18, 33, 59. For the Redstone: "This Is Redstone," Chrysler Corporation Missile Division, II-43. Downloaded from <http://www.myarmyredstonedays.com/page12.html>.

45. *Vengeance Weapon 2*, Appendices 1, 3.

46. *Redstone History*, 98.

47. *Vengeance Weapon 2*, 27.

48. *Redstone History*, 173.

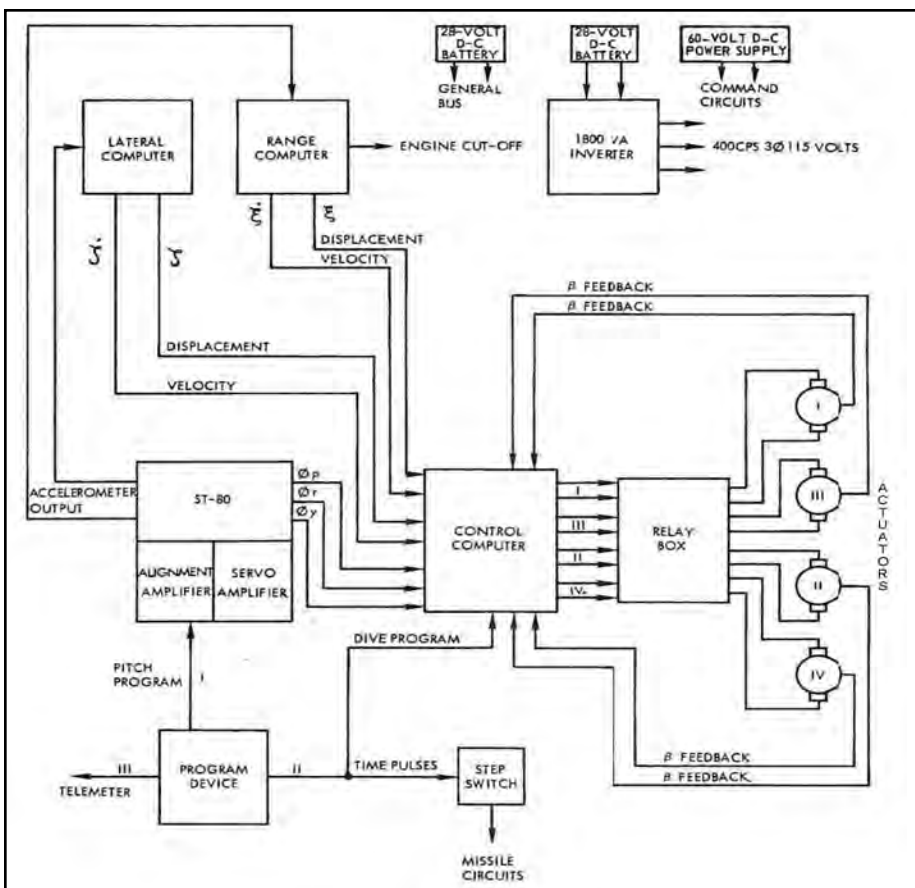


Figure 23. Redstone Guidance and Control System. 55

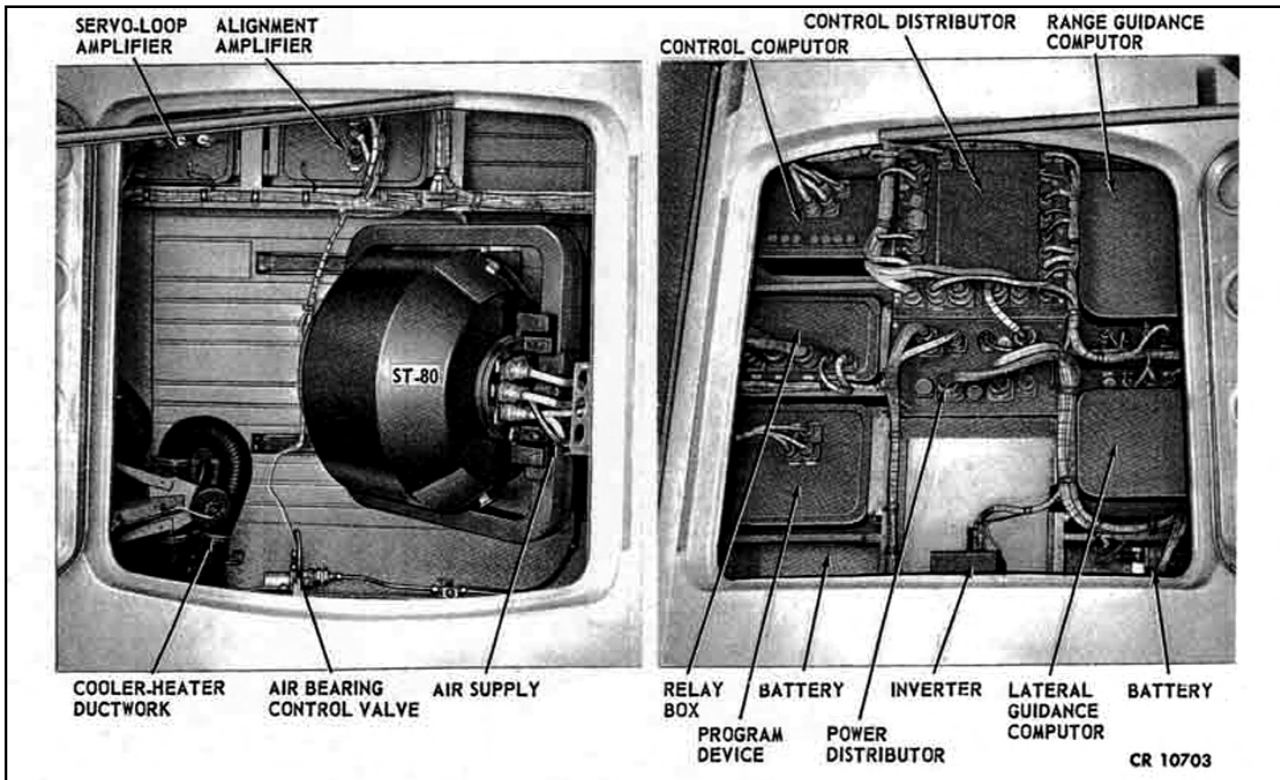


Figure 24.

Interior of the Redstone instrument compartment.⁵⁶

49. *This Is Redstone*, Chapter IV.

50. "The Redstone Missile System", [August 1960], 3, Figure 1. PDF version of 38-page paper document from the Morris Swett Library, US Army Field Artillery School, Fort Sill, OK. Downloaded from <http://www.myarmyredstonedays.com/page12.html>.

51. *This Is Redstone*, IV-0.

52. Walter Haeussermann and Robert Clifton Duncan, "Status of Guidance and Control Methods, Instrumentation, and Techniques as Applied in the Apollo Project," Chapter 2, *Launch Vehicle Inertial Navigation and Guidance*, NASA [1964]. To be presented at the lecture series on orbit optimization and advanced guidance instrumentation, Advisory Group for Aeronautical Research and Development, North Atlantic Treaty Organization, Duesseldorf, Germany, October 21-22, 1964. Page 2-22: "To obtain a simple computation scheme, a coordinate system that permits guidance and cutoff equations without cross coupling terms has been selected."

53. Oral history of Fritz Mueller taken by Michael Neufeld at National Air and Space Museum, 6 November 1989, 65.

54. *This Is Redstone*, IV-2 and IV-8.

55. *This Is Redstone*, Figure IV-2, IV-4.

56. U.S. Army Technical Manual TM 9-1410-350-14/2 [September 1960]. Downloaded

from *My Army Redstone Days*, http://www.myarmyredstonedays.com/Photos/page8/shell_06.html.

57. *This Is Redstone*, IV-12.

58. US Patent 2,963,242 issued 6 December 1960 to Fritz K. Mueller for a stabilized platform with internal gimbals.

59. *Mueller history*, 26.

60. *Saturn V Flight Manual SA-507*, Figure 7-16, page 7-18.

61. *This Is Redstone*, IV-2.

62. *This Is Redstone*, IV-3.

63. Farrior, 154. Ernst Stuhlinger, "Army Activities in Space--A History." *IRE Transactions on Military Electronics*, April-May 1960, 65.

64. *Backfire*, Volume 2 Plate 65, circuit diagram for the control amplifier.

65. "Supplement #1 to Volume IV Redstone Field Artillery Guided Missile System. 30 June 1955 through 30 September 1956," NARA, RG 156, Entry 1039, Box 29, 2.

66. "Supplement #1 to Volume IV Redstone Field Artillery Guided Missile System. 30 June 1955 through 30 September 1956," NARA, RG 156, Entry 1039, Box 29.

67. *This Is Redstone*, Chapter IV

68. Haeussermann 5-81, Figure 17, 235. Reprinted with permission of the American

Institute of Aeronautics and Astronautics.

69. Herman E Thomason, "A General Description of the ST124-M Inertial Platform System." NASA MSFC [September 1965], NASA TN D-2983. Dimensions for the gyros used in the ST-124 are on page 57.

70. *Redstone History*, pages 69-70 lists thirteen launches carrying the LEV-3.

71. Oral history of Walter Haeussermann recorded 24 January 1990 at Huntsville, AL by Michael Neufeld. NASM, 36.

72. Wernher von Braun; "The Redstone, Jupiter and Juno." *Technology and Culture*, Vol. 4 No. 4, *The History of Rocket Technology* (Autumn 1963), 452-465. Published by The Johns Hopkins University Press on behalf of the Society for the History of Technology, 457.

73. *Redstone History*, Figure 2, 166-167.

74. *Mueller history*, 39.

75. Finkle.

Figure 28. Internal gimbals used in the ST-80.⁵⁹

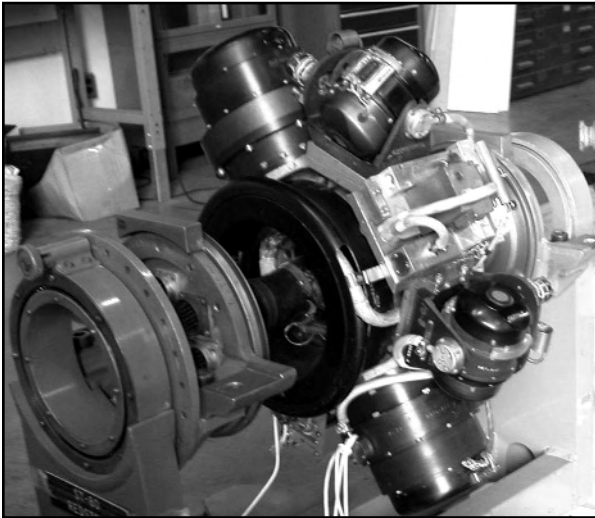
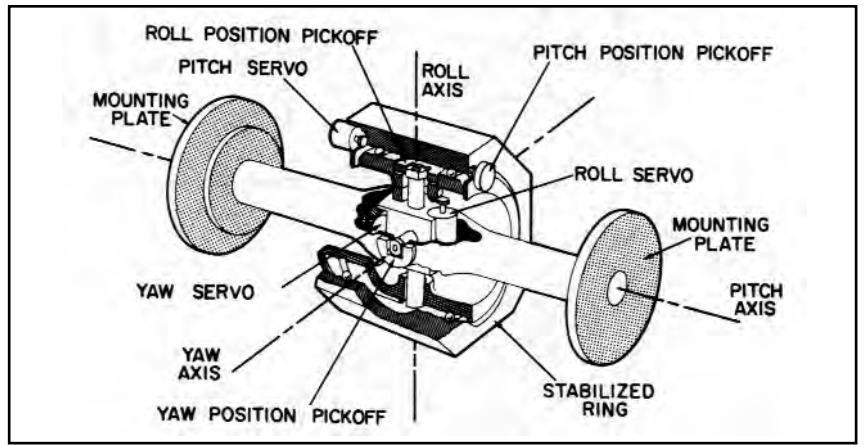


Figure 25. ST-80 in the collection of NASM, with its cover removed.

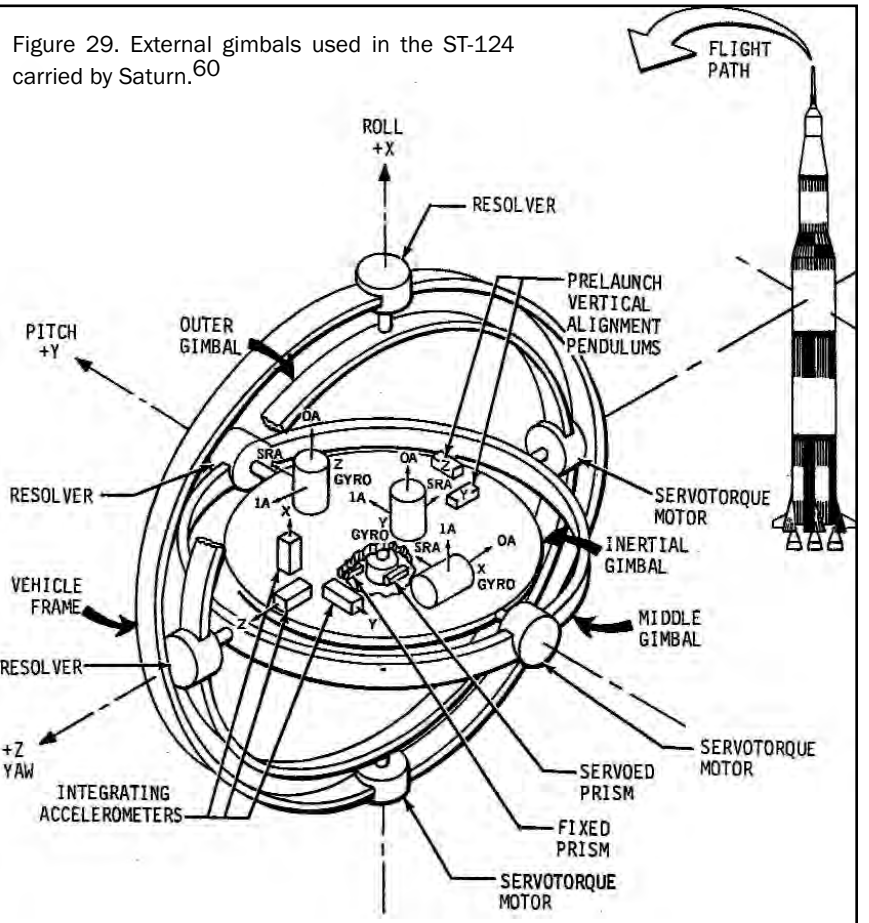


Figure 29. External gimbals used in the ST-124 carried by Saturn.⁶⁰

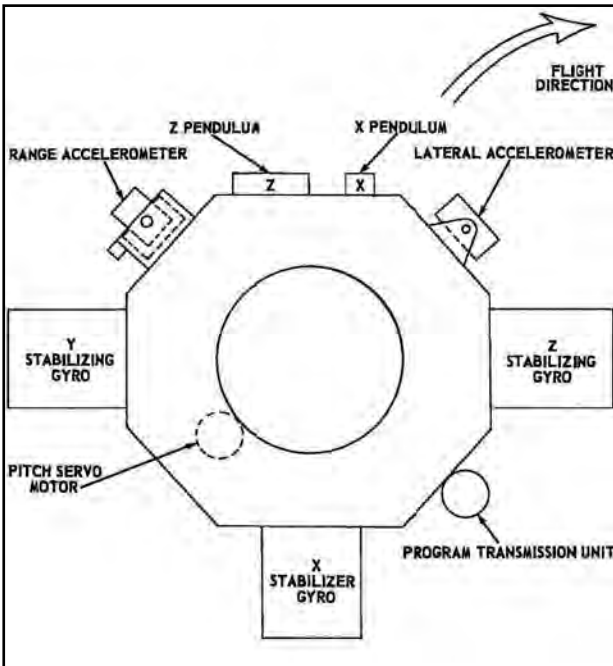


Figure 26. Section of Redstone stabilized platform perpendicular to the pitch axis.⁵⁷

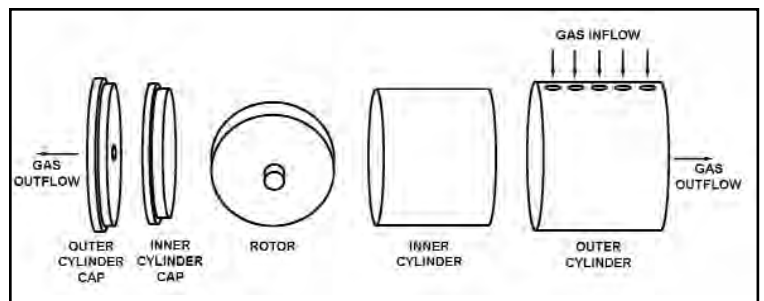


Figure 31. Gyro with gas bearing.

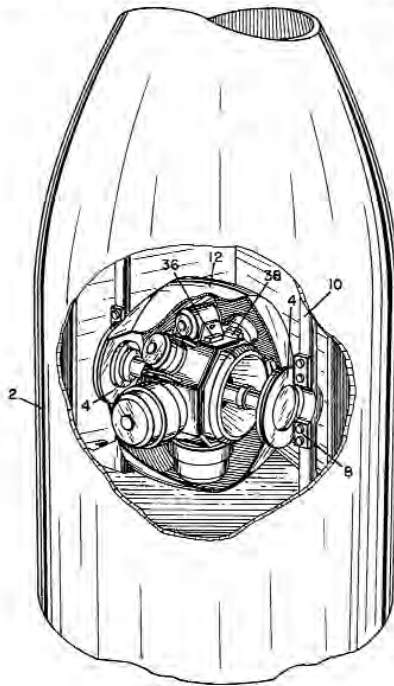


Fig. 1

FRITZ K. MUELLER,
INVENTOR.

Figure 27. Patent figure showing orientation of stabilized platform in the missile nose.⁵⁸

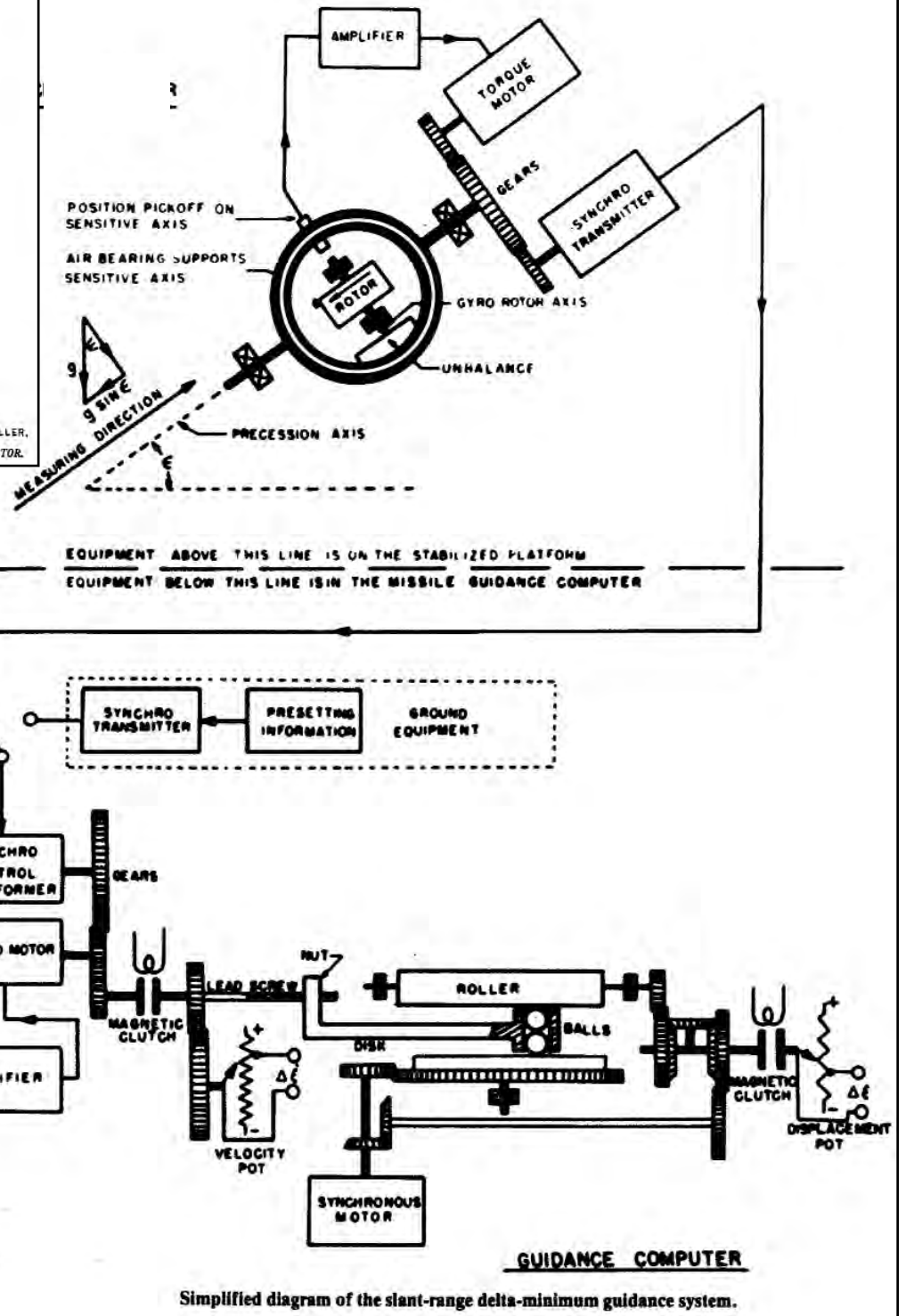
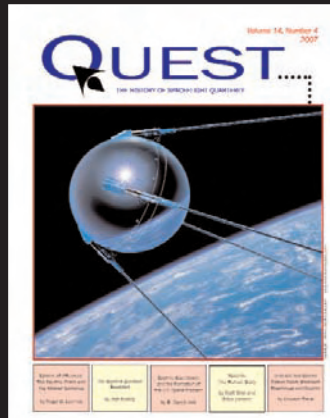


Figure 30. Redstone guidance computer.⁶⁸

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