Volume 17, Number 4
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QUEST

THE HISTORY OF SPACEFLIGHT QUARTERLY

Contents

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Front Cover Image Caption and Credit

A fish-eye lens view showing astronauts Alan B. Shepard Jr. and Edgar D. Mitchell in the Apollo lunar module mission simulator at the Kennedy Space Center during preflight training for the *Apollo XIV* lunar landing mission, 15 July 1970. Credit: NASA

Back Cover Image Caption and Credits

(clockwise, top left)

Propped by a kickstand while its passengers embark on pedestrian explorations, this imaginary rover is a rubber inflatable with a belt around its middle that serves as a spare tire and a bumper. The solar array "parasol" suspended above the unicycle rover is fitted with solar batteries to collect and store energy for all the rover's systems. Artist: Frank Tinsley, *Aviation Week*, 16 February 1959.

The Lummus Company ad depicts a test chamber on Earth for simulating the lunar environment. *Missiles and Rockets,* 3 September 1962.

The idea of space tourism would naturally imply a need for lodging, but in Thompson's ad the "space motel" mentioned refers to a space station that would serve as a "motel" for rockets and as a long-term habitation module for astronauts. Artist: Don Hinkley, *Business Week,* 12 July 1958

A von Braunian wheel-shaped space station hovers in orbit around the Moon, a variation on the space station as stepping stone in the form of an Earth-orbiting workshop for assembly of lunar and interplanetary spacecraft. *Aviation Week,* 13 July 1959.

All images courtesy of Blast Books and appear in the book, *Another Science Fiction: Advertising the Space Race 1957—1962.*

FEATURE

Saturn I Guidance and Control Systems

by Edgar Durbin

Introduction

The vehicle that carried Americans to the Moon from 1969–1972 was proposed by the Wernher von Braun group at Redstone Arsenal to the Department of Defense (DoD) in December 1957.[1] The scope of the proposal was broader than a mission to the Moon: it was "an integrated missile and space program" for the United States. Its objectives were scientific and technological supremacy, space warfare capability, and space exploration.

The proposal came on the heels of the Soviet Union's successful orbit of *Sputnik I* on 4 October 1957, and America's failure to launch Vanguard on 6 December. The DoD's new Advanced Research and Projects Agency (ARPA) replied to the Redstone proposal in October 1958 with funding for development of "a large space vehicle booster of approximately 1.5 million pounds thrust based on a cluster of available rocket engines." The vehicle authorized by ARPA was intended for a variety of missions, including space defense, large satellite launch, a troop carrier for missions on Earth, an intercontinental ballistic missile (ICBM), scientific research, space probes, and humans in space missions.[2] Eventually the vehicle was named Saturn,[3] and the missions were limited to humans in space missions (Apollo, Apollo-Soyuz Test Program, and Skylab). Although the Moon landing program was proposed by President John F. Kennedy on 25 May 1961 in a speech at a special joint session of Congress, by that time, the Saturn had been in development for two and a half years. The Saturn program lasted for 18 years, until 1975.[4]

There were three Saturns: Saturn I, Saturn IB, and Saturn V. They are compared in Figure 1.

Saturn I was the research-and-development vehicle, and Saturn IB and Saturn V were the operational vehicles, used to launch human missions. Figure 1 compares the three vehicles for a common task, insertion of a payload into low Earth orbit. In practice, Saturn V performed this mission only once, for launch of the orbital workshop during the Skylab program. Most of the Saturn V launches were used for translunar injection during Apollo missions.[6]

Saturn I had two configurations, called Block I and Block II, which are compared in Table 1 and Figure 2. A vehicle consisted of several stages, stacked one on the other. For example, the first stage of Saturn I Block II was the S-I, a cluster of eight 70-inch propellant tanks surrounding a single 105-inch tank

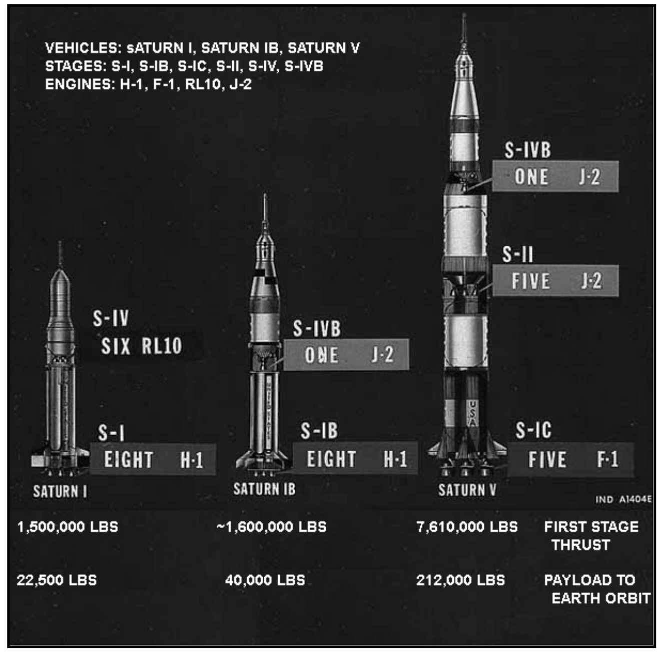


Figure 1. Saturn I, IB, and V compared.[5] Block I Saturn I carried dummy stages in place of S-IV. Saturn V for Skylab carried an orbital workshop in place of S-IVB.

feeding eight engines. The second stage was the S-IV, which had a single liquid oxygen tank and a single liquid hydrogen tank feeding six engines. The instrument unit was the third and last stage in the Saturn I Block II stack. Above the instrument unit was the Apollo spacecraft. The complete vehicle was a Saturn rocket and an Apollo spacecraft. Ten Saturn I vehicles, SA-1 (Saturn–Apollo 1) to SA-10, were launched from Cape Canaveral Launch Complex 34 (LC-34) and Launch Complex 37B (LC-37B).

Scope

This article describes the guidance and control system used in the Saturn I vehicles. The Saturn launch vehicle was steered by swiveling its engines. Actuators could move four of the eight H-1 engines in the S-I stage through ±7 degrees.[8] A similar system of actuators moved the six RL-10 engines of the S-IV stage through ±4 degrees.[9] The actuators received commands from the flight control computer, an analog device that converted data from the digital guidance computer and from control sensors into actuator commands. The guidance comput-

Table 1. Saturn I Block I and Block II

	Block I	Block II
Powered stages	One: S-I	Two: S-I and S-IV
Trajectory	Sub-orbital	Earth orbit
Location of guidance components	Four canisters in forward part of S-I stage	Instrument Unit on top of S-IV stage
Flight program	Pitch only	Roll and pitch
Fins	None	4 large and 4 small
Launch complex	LC-34	LC-37B
Missions	SA-1 to -4	SA-5 to -10

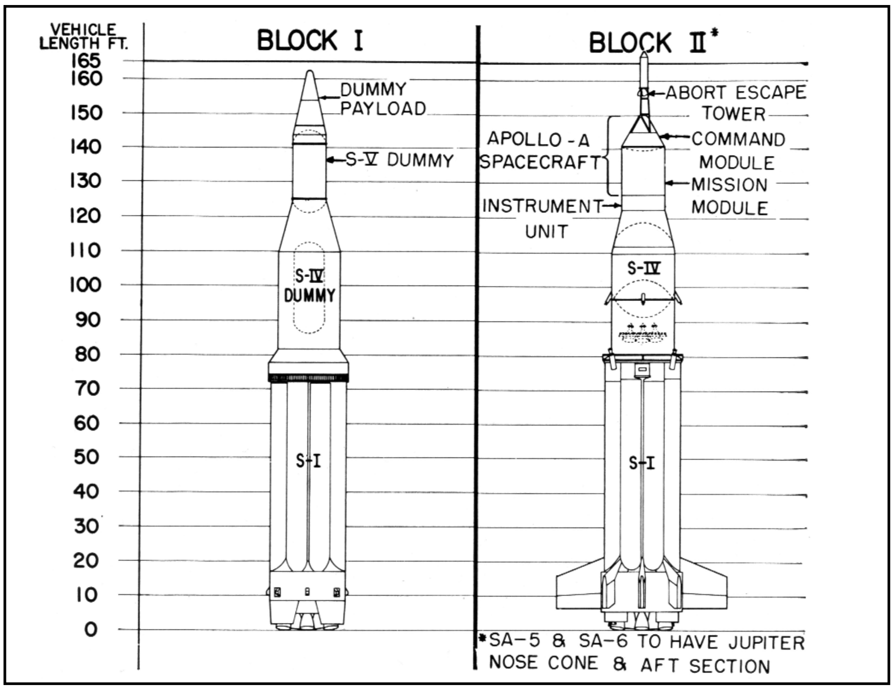


Figure 2. Diagram of Block I and Block II of Saturn I [7]

er calculated necessary changes in vehicle attitude from data received from inertial sensors carried on the stabilized platform. The trajectory was determined for early vehicles by a mechanical cam device and for later vehicles by a program loaded on the guidance computer.

The basic guidance system thus consisted of a program defining the target trajectory (specified either by the shape of the cam or by a program stored in the guidance computer), sensors to measure vehicle orientation and velocity, and a digital computer to solve the guidance equation and calculate changes in attitude needed to follow the target trajectory.

The control system included angle-of-attack sensors, attitude rate sensors, control accelerometers, the analog flight computer, and actuators to tilt the engines.

System Development

Figure 3 through Figure 7 show the evolution of the guidance and control system from SA-1 through its final version in SA-10. The major themes of development were as follows:

· **Passenger vs. active**—Several components first flew on Saturn I as passengers, not influencing vehicle motions, but only collecting data that were telemetered to ground for analysis. In later missions, some of these components became active; that is, they provided data to the control and guidance system.

· **Tilt program**—All Saturns flew a trajectory that was a function only of time during passage through the atmosphere, when aerodynamic forces were greatest. The pitch of early vehicles was controlled by a cam device, whose shape constituted the tilt program. Later vehicles carried a tilt program in the digital guidance computer as a set of coefficients of a power series. During this first phase of flight, guidance sensors only telemetered data to the ground without influencing the trajectory of the vehicle.

· **Roll program**—Block I missions did not have a roll program, though there was some uncontrolled roll due to thrust imbalance. Block II missions, which left from a different launch complex, had to roll after liftoff to the proper azimuth.

· **Digital computer**—The digital guidance computer, flown as a passenger on SA-5 and -6, replaced the cam device (for the tilt program) and the program device (for sequence timing), and made active guidance possible, starting with the second stage of SA-6 and continuing on all subsequent missions. It also made a combined roll–tilt program possible, starting with SA-7.

· **Stabilized platform**—The ST-90 stabilized platform, used in Jupiter missiles and flown on SA-1 to -6, was replaced on SA-7 by the ST-124, designed for the Moon mission. (A stabilized platform is a gyroscopic device for measuring vehicle velocity and attitude in a space-fixed coordinate system.)

· **Control sensors**—Angle-of-attack data used for control on the first three missions was replaced by accelerometer data for the fourth and subsequent missions. (Angle of attack is the angle between the vehicle's longitudinal axis and the air flow past the vehicle.)

· **Instrument Unit**—Block I vehicles carried guidance and control sensors in four pressurized containers housed in the forward part of the S-I stage. These sensors were carried by Block II vehicles in a new stage, the Instrument Unit, which stacked on top of the S-IV stage. SA-5, -6, and -7 carried the first version of the Instrument Unit; and SA-8, -9, and -10 carried the second version.

These developments are shown in Figure 3, which summarizes information

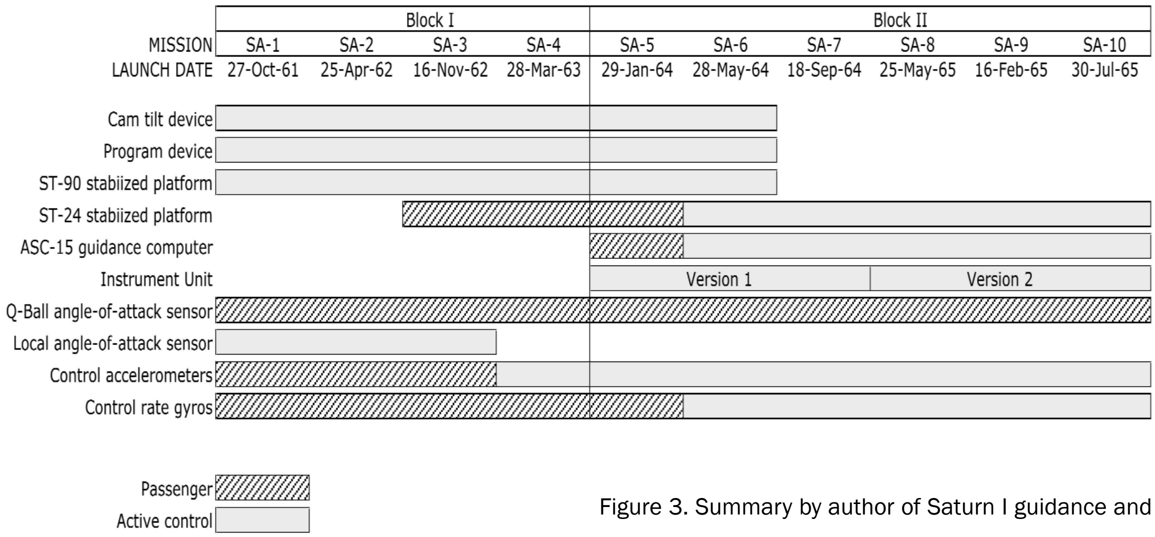


Figure 3. Summary by author of Saturn I guidance and control components

from more than a dozen technical reports written during the Saturn program.

Figure 4 to Figure 7 are original system diagrams from fight evaluation reports and other contemporary technical documents edited for clarity.

Control System

The control system sensed deviations from the attitude specified by the guidance system (pitch, roll, and yaw) and commanded changes in the direction of thrust to counter them. The Saturn I Block I vehicle was unstable during part of its flight, because the center of pressure of aerodynamic forces on the vehicle was forward of its center of mass.[15] A small increase in the angle of attack (for example, due to wind) would cause vehicle rotation, which further increased the angle of attack. If not corrected, the vehicle would tumble. The addition of fins at the bottom of the first stage in Block II improved stability by moving the center of pressure aft of the center of mass during the first minute of flight.[16] However, active control was still necessary and was employed throughout a mission.

The flight control computer received outputs from several sensors, which varied with mission. For the first three missions, angle of attack measured by sensors in the nose cone was combined with data from sensors carried in the ST-90 stabilized platform. Beginning with SA-4, control accelerometers were used instead of angle-of-attack sensors.[17]

For SA-1 to -3 the control computer calculated the swivel angle of the engines using the equation

$\beta = a_0*\phi + a_1*d\phi/dt + b_0*\alpha$ where

β is the swivel angle,

ϕ is the error in the vehicle attitude angle determined by the guidance system,

α is the angle of attack, and a_0, a_1, and b_0 are gains, which change during flight.[20]

The heading error ϕ was supplied

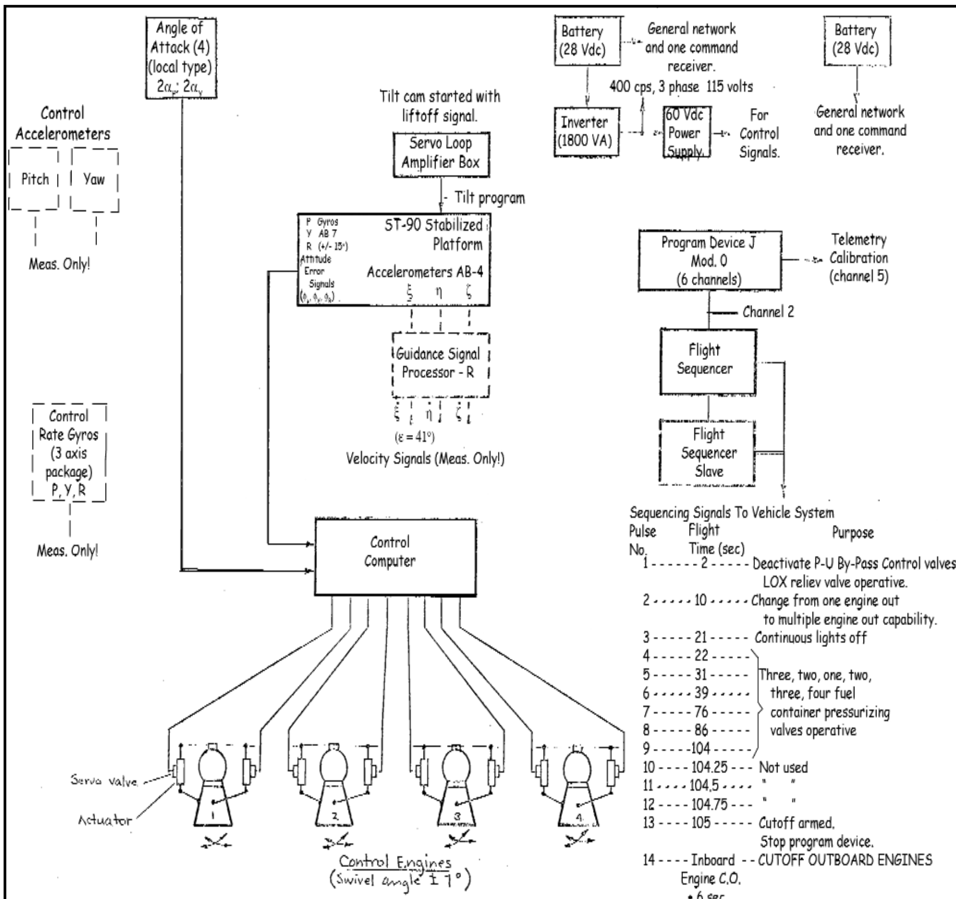
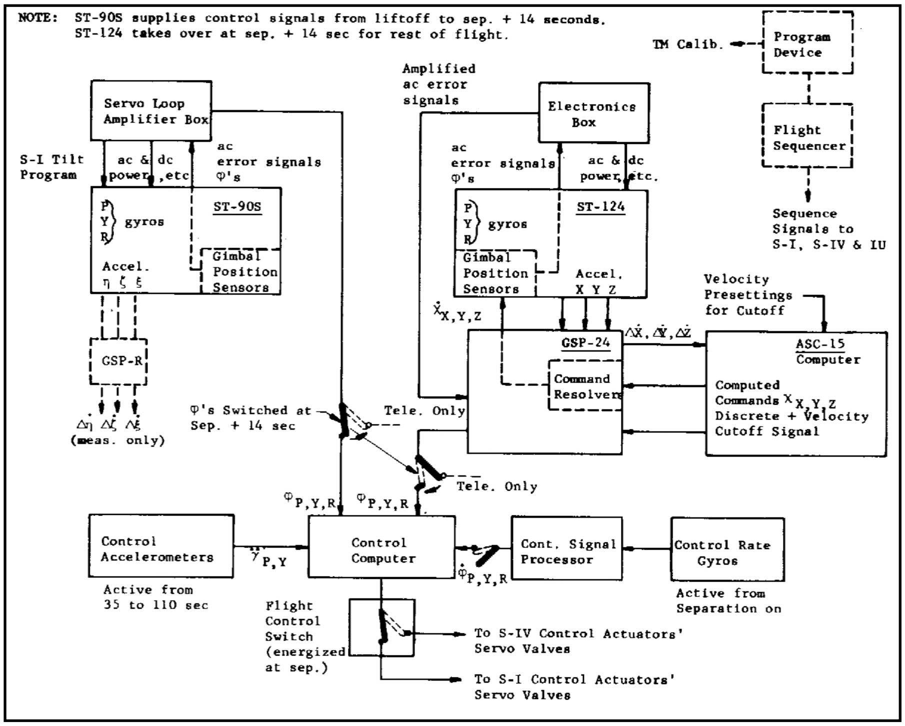


Figure 4. SA-2 Guidance and Control System.[10] This is essentially the same as the system used on SA-1 and SA-3.[11] Boxes with dashed lines and "Meas. Only!" indicate passenger components.



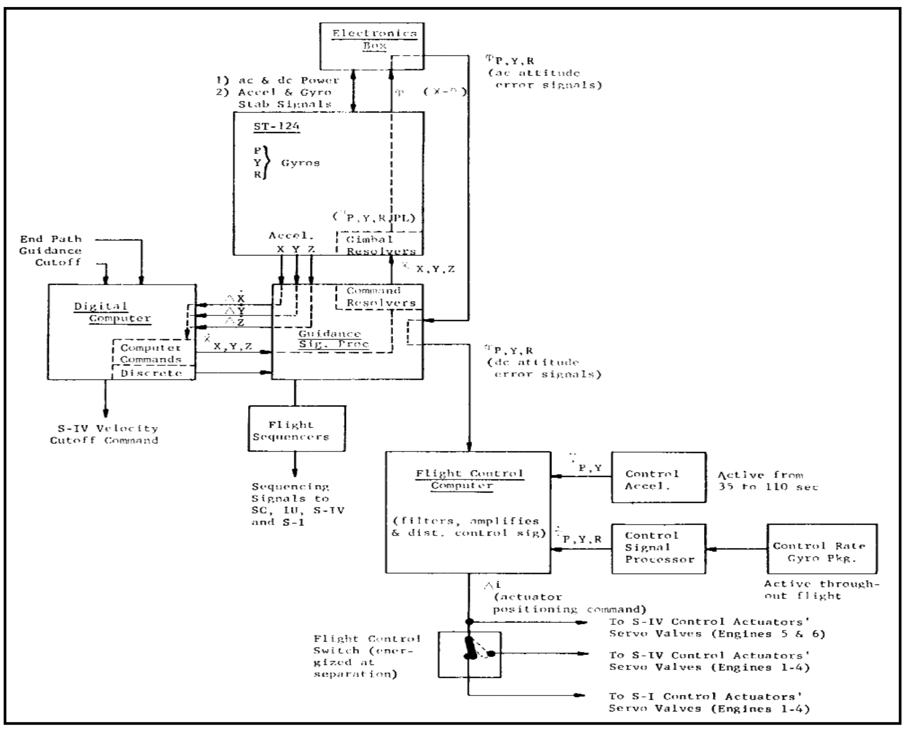


Figure 5. [top] SA-6 Guidance and Control System[12] The system on the left controlled the first stage, and the system on the right controlled the rest of the mission.

Figure 6. [bottom] SA-7 Guidance and Control System[13] Same as the second stage guidance used on SA-6: no program device, ST-90, or tilt cam.

by the ST-90 stabilized platform. Networks of resistors and capacitors in the control computer calculated the heading error rate $d\phi/dt$.[21]

Beginning with SA-4, instead of angle of attack, the control computer used lateral accelerations measured by body-fixed control accelerometers. The control equation was then

$$\beta = a_0*\phi + a_1*d\phi/dt + g_2*d^2\gamma/dt^2$$

where $d^2\gamma/dt^2$ is the acceleration of the vehicle normal to its long axis and g_2 is a gain.[22]

Control feedback stability analyses[23] and a mathematical condition called the Drift Minimum Principle (DMP)[24] were used to calculate the gains. The DMP caused the vehicle to head into the wind slightly, reducing the angle of attack by about 50 percent, so that the lateral component of the gimbaled engine thrust just opposed the lateral aerodynamic force.

In addition to gain (change in amplitude of the sensor signals), the control computer introduced a shift in phase that was critical to achieving stability. The appropriate phase had been investigated theoretically by modeling the electrical circuits in the control system, the mechanical components (actuators, engine gimbals), and the vibrations of the vehicle structure. This system was a closed loop, and could either tend to the orientation specified by the guidance computer or diverge if gain and phase were wrong. In the latter case, the control system would over-correct for winds or other random disturbances and provoke oscillations that could lead to vehicle breakup. To keep the system in the region of stability, the signals from the sensors were passed through phase shaping networks in the control computer.

Gains varied during a mission and from mission to mission. Potentiometers and resistors switched by relays within the control computer determined the gains (a_0, a_1, and either b_0 or g_2). A synchronous motor rotated a cam that rotated the potentiometers. The shape of the cam grooves and the times when the motor was turned on and off determined the way that the gains varied.[25] Figure 10 shows the two methods of setting control gain.

Figure 11 shows the gains used on SA-2.

SA-2 was controlled only in response to signals from the ST-90 stabilized platform for the first 25 seconds of flight. After that time, the gain for the angle-of-attack signal increased to a maximum between 50 and 70 seconds, then declined to zero again at 90 seconds. Comparing Figure 11 and Figure 12 shows that the angle-of-attack sensor was

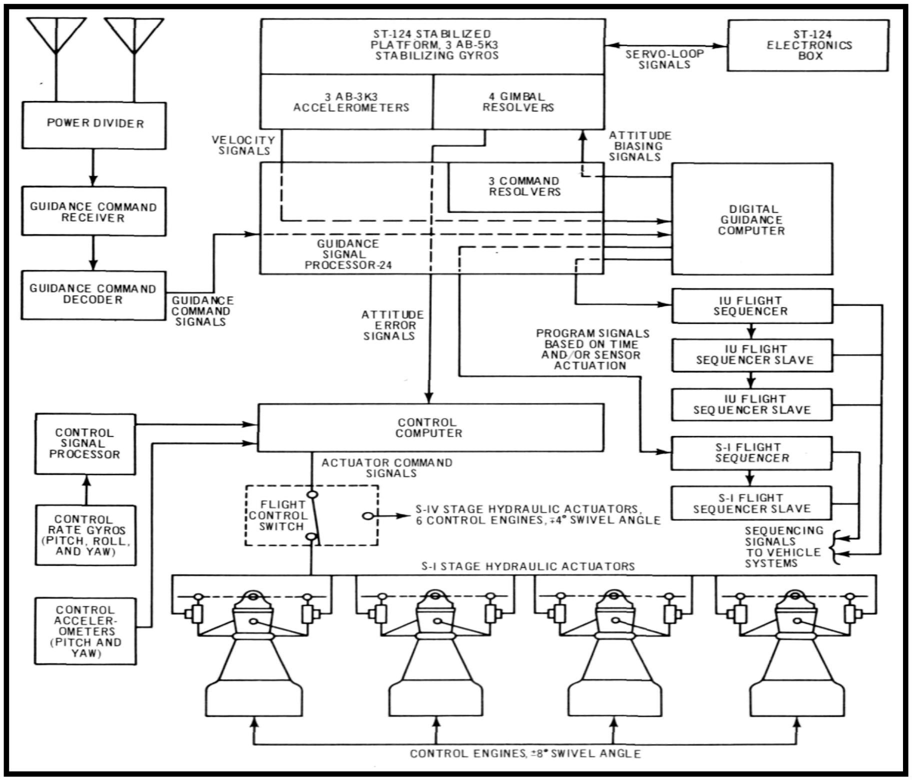


Figure 7. SA-8, -9, and -10 Guidance and Control System[14]

used during the period of high dynamic pressure. The sensor was considered unreliable after about 105 seconds, due to low dynamic pressure.[30] Other missions showed similar gain profiles. See Figure 13 for the behavior of control gains with time on the operational Saturn IB vehicle.

Block I Guidance

The guidance systems for Block I vehicles (SA-1 to -4) were simplified, since these were suborbital missions, their azimuths were fixed by the launch pad configuration, and they had a single powered stage (S-I). As with all Saturn launches, the early part of flight, when aerodynamic forces were greatest, followed a preset path, designed to minimize lateral forces.[32] This tilt program was determined by the shape of a groove in a cam device housed in the servo loop amplifier box.[33] This cam device is shown in Figure 14.

Saturn had defined roll, yaw, and pitch axes (X, Y, and Z, respectively) as shown in Figure 15. Its preferred roll attitude had Positions I and III in a vertical plane, with Position I pointing down toward Earth when the vehicle was horizontal in orbit. The Z axis passed through Position I (also known as Fin I in Block II), and at LC-34 it pointed approximately 100 degrees 12 minutes east of north. At LC-37B the Z axis pointed at approximately 90 degrees 12 minutes east of north.[35] The Y axis was perpendicular to X and Z and was horizontal at launch, pointing roughly south.

The engines were canted to approximately direct their thrust through the vehicle's center of gravity. This diminishes the tendency to rotate caused by an engine outage or thrust imbalance.

Because of the orientation of LC 34, Block I vehicles could be launched with no roll maneuver. Figure 16 shows that this meant that S-band, AZUSA, and C-band antennas faced downward, toward the ground tracking stations with which they communicated. Positions I, II, III, and IV in Figure 16 are the same as in Figure 15.

Block II Guidance

The orientation of LC-37 made it necessary for Block II vehicles to roll before pitching over in the plane of the orbit. The amount of roll depended on the launch azimuth, which was a function of launch time. The vehicle's trajectory was in a plane that contained the center of Earth, the launch site, and the position of the Moon at the time of insertion into Earth orbit.[39] Any other orbital inclina-

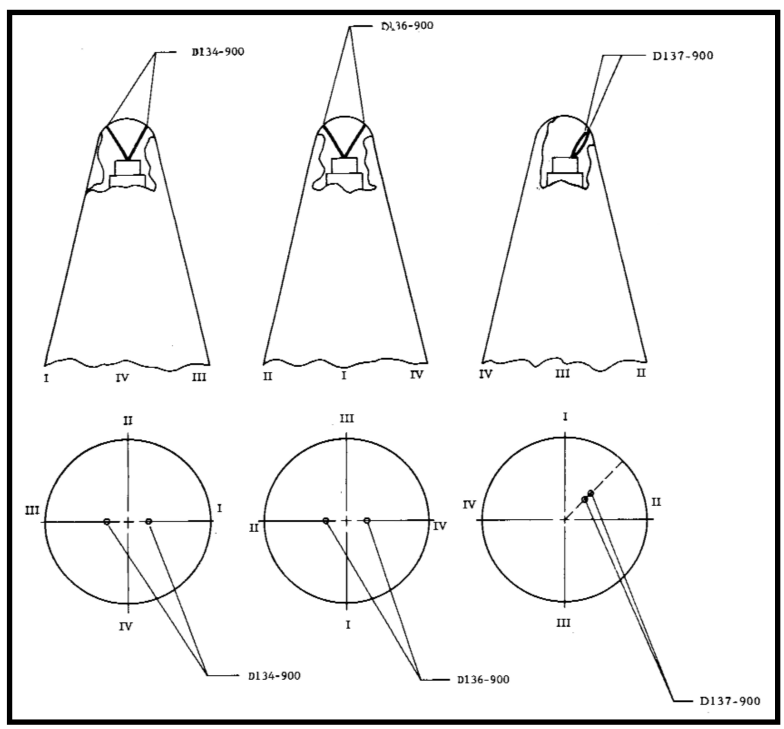


Figure 8. Q-Ball Angle-of-Attack Sensors (passenger only)[18] Comparing the dynamic pressures at six different points on the nose cone allowed calculation of the direction from which air flowed over the vehicle.

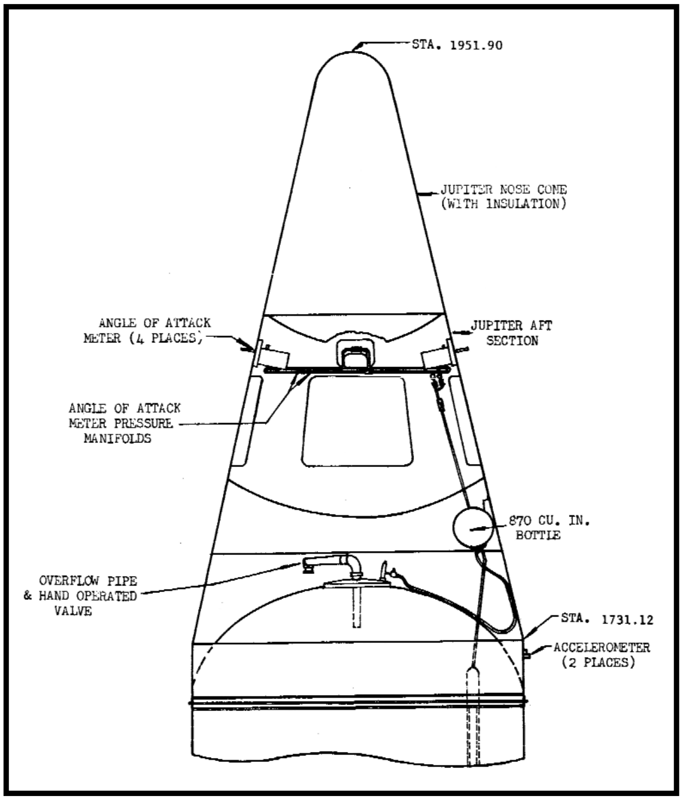


Figure 9. Local Angle-of-Attack Sensors. These controlled the flights of SA-1, -2, and -3.[19]

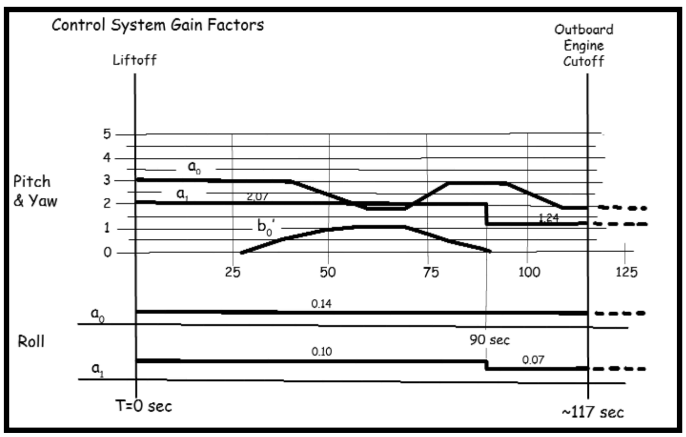


Figure 11. Control Gains for SA-2[28]

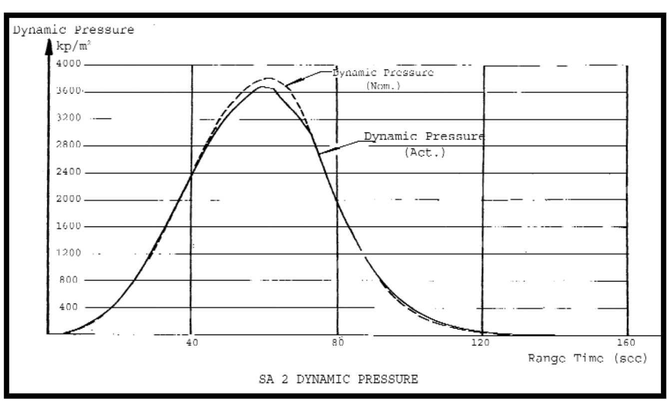


Figure 12. Dynamic Pressure vs Flight Time for SA-2.[29]

tion would require out-of-plane maneuvers, which would cost precious fuel. During countdown, this plane moved, because the Moon moved, so the roll maneuver and launch azimuth were functions of the launch time.

The external azimuth alignment system adjusted the orientation of the stabilized platform continuously during countdown to keep the ξ axis of the stabilized platform pointed at the launch azimuth. The program device, a precision multitrack tape player holding sequence data, started at liftoff, and after a delay to allow the vehicle to clear the launch tower, it signaled the flight sequencer to close the servo loop, and the roll maneuver began.[40] It stopped when the signal from the stabilized platform ended as the vehicle reached the flight azimuth. Shortly after, the program device signaled the start of the tilt cam device.

For SA-5 and for the first stage of SA-6, mechanical devices as described above controlled roll and tilt. From SA-7, a

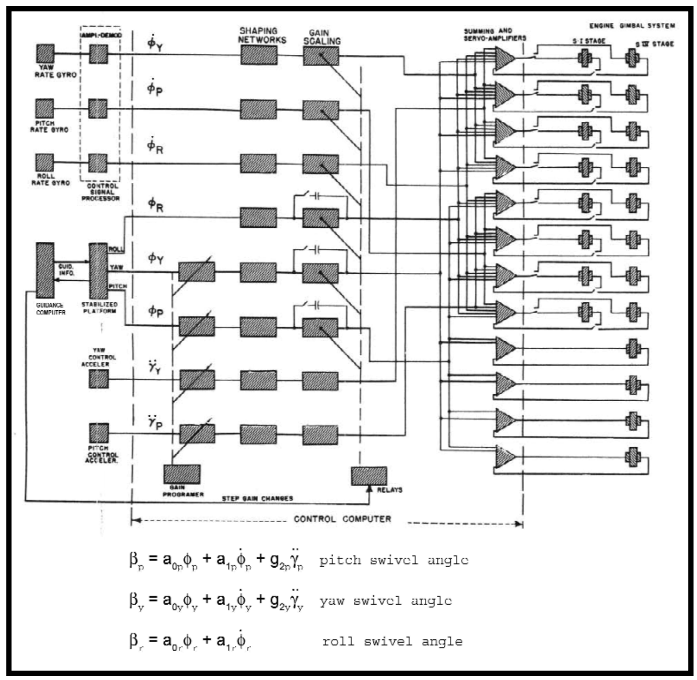


Figure 10. Saturn I Control System[26] This figure comes from an article that describes "Gain Programmer" as "a simple cam mechanism driven by a synchronous motor. The cam positions a potentiometer to set the gain in each channel." In the *Astrionics System Handbook* (1968) this device is called the Control Attenuation Timer (CAT).[27]

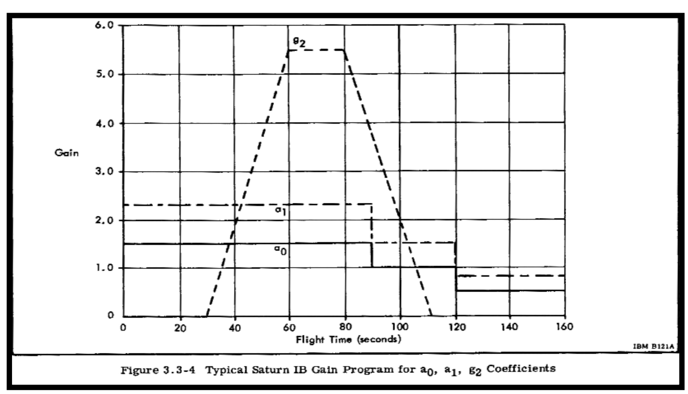


Figure 13. Saturn IB Control Gains.[31]

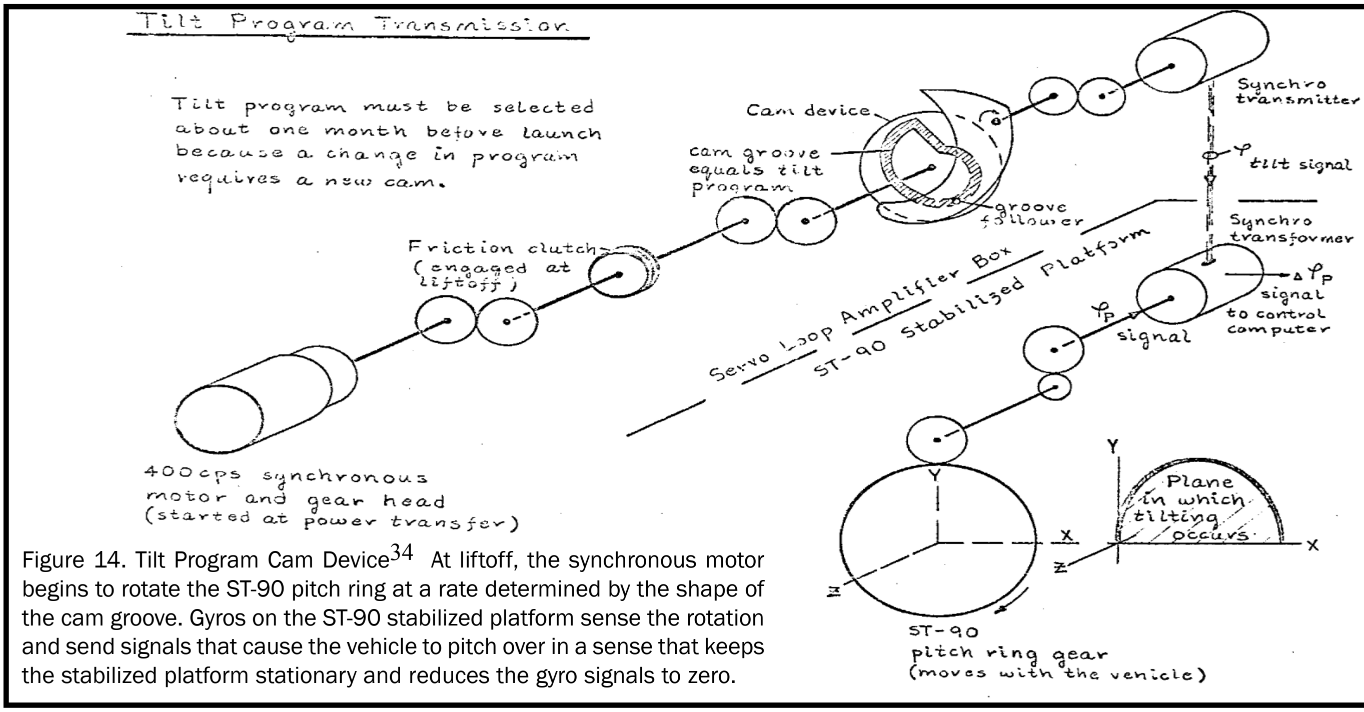


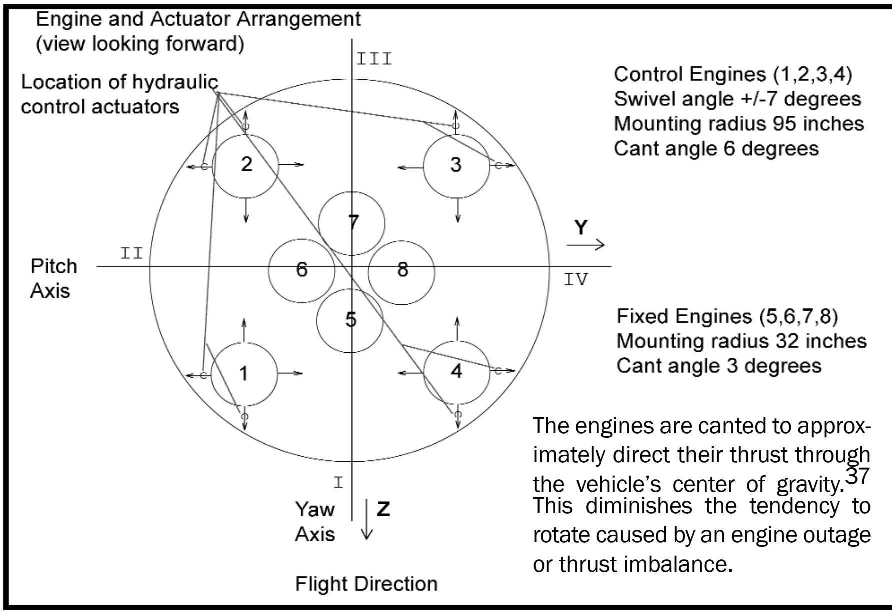
Figure 14. Tilt Program Cam Device[34] At liftoff, the synchronous motor begins to rotate the ST-90 pitch ring at a rate determined by the shape of the cam groove. Gyros on the ST-90 stabilized platform sense the rotation and send signals that cause the vehicle to pitch over in a sense that keeps the stabilized platform stationary and reduces the gyro signals to zero.

digital guidance computer replaced the program device and the cam tilt device.[41] Roll and tilt maneuvers were then performed together, rather than sequentially. Roll was completed within the first 30 seconds of flight, but pitch increased continuously almost until insertion into orbit. Since tilt was calculated by evaluating a polynomial, the tilt program was easily changed between missions by loading the computer with different coefficients. Reprogramming the cam tilt device required a month, because a new cam had to be machined.[42]

The digital flight computer made active guidance possible: guidance depended on flight conditions, not just time. The guidance equations were solved once a second, and the optimum vehicle attitude was sent to the flight control computer to create commands for the engine actuators. Roll, yaw, and pitch required separate guidance solutions.

Once the correct roll attitude had been achieved, the flight control system maintained it fixed. No guidance calculations were necessary for roll, because the correct value was determined at launch and remained constant for the rest of the mission.

The vehicle yawed when it point-



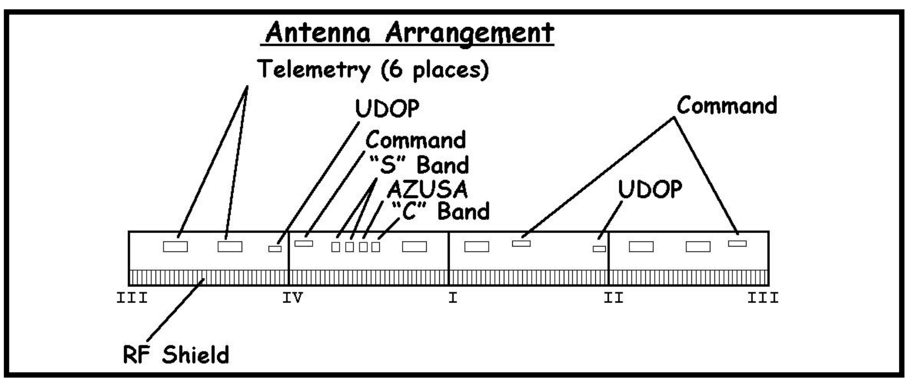


Figure 15. [top] Body-fixed Coordinates for SA-2.[36]

Figure 16. [bottom] SA-2 Antennas.[38]

PARAMETER	VARIATION
Propellant weight	+/- 500, +/- 1,000, -2,500, and -5,000 kg
Structure weight	+2,500 and +5,000 kg
Headwind	3σ
Tailwind	3σ
Right crosswind	3σ
Engine no. 3 out	100 s
Thrust and mass flow	+/- 1%
Isp (average specific impulse)	+/- 1%

Table 2. Perturbations Used for SA-7 Studies[46]

ed out of the orbit plane. Yaw varied little from zero, and used the simplest guidance mode, called delta minimum guidance. The steering equation for yaw was a linear function of displacement from the orbit plane and the time derivative of this displacement.

The vehicle pitched when it rotated in the orbit plane from vertical toward the horizon. Pitch varied more than yaw or roll, and determining optimum pitch was a more difficult problem. The first scheme for pitch guidance flown on Saturn I was the polynomial guidance mode or PGM, used on the second stage of SA-6 and the entire powered flight of SA-7.[43] An improved scheme, the iterative guidance mode or IGM, was used on the rest of Saturn I, IB, and V missions. PGM and IGM are both examples of adaptive guidance.

The initial part of a Saturn mission flew open loop,[44] without active guidance, to reduce aerodynamic forces during passage through most of the atmosphere. The guidance system determined the desired attitude using only the time from launch. It did not take account of variations in thrust, wind, or other disturbances. Active guidance began after the second stage (S-IV) had ignited, about 165–168 seconds after liftoff.[45] At this point the vehicle altitude was about 90 kilometers, well above the point of maximum dynamic pressure at 11–12 kilometers. While the position at the ignition of the first stage was known, because of variations in flight conditions during the first-stage burn, the point where active guidance began might be anywhere in a considerable volume of space. A family of minimum fuel trajectories was therefore calculated in the months before launch which started at different points in this volume, with various values of velocity and attitude. Table 2 shows the variations used to generate the trajectories for SA-7.

An optimum trajectory, with given starting and ending points, could be determined using the calculus of variations with a large digital computer and substantial time. Because it was beyond the capabilities of the onboard digital computer to use calculus of variations techniques, the results of computations performed on the ground were summarized by a polynomial approximation to the optimum steering angle. The coefficients of the polynomial were derived by regression analysis of the set of optimum trajectories.[47] The variables of the polynomial were the quantities measured by onboard devices: position, velocity, and acceleration. The polynomial was of the third power, and had about 35 terms. Such polynomials, one for pitch and one for yaw steering angle, were evaluated once a second, with updated values of position, velocity, and acceleration. This scheme for guidance was

Table 3. History of Saturn Launches

PROGRAM	VEHICLE	MISSION	LAUNCH DATE	PAD	IU VERSION	RESULT[51]
Saturn I	SA-1	SA-1	27-Oct-61	34	-	Sub-orbital
Saturn I	SA-2	SA-2	25-Apr-62	34	-	Sub-orbital water release
Saturn I	SA-3	SA-3	16-Nov-62	34	-	Sub-orbital water release
Saturn I	SA-4	SA-4	28-Mar-63	34	-	Sub-orbital
Saturn I	SA-5	SA-5	29-Jan-64	37B	1	Orbit of second stage
Saturn I	SA-6	A-101	28-May-64	37B	1	Orbit of Apollo spacecraft
Saturn I	SA-7	A-102	18-Sep-64	37B	1	Orbit of Apollo spacecraft
Saturn I	SA-9	A-103	16-Feb-65	37B	2	Orbit of Pegasus satellite
Saturn I	SA-8	A-104	25-May-65	37B	2	Orbit of Pegasus satellite
Saturn I	SA-10	A-105	30-Jul-65	37B	2	Orbit of Pegasus satellite
Saturn IB	SA-201	AS-201	26-Feb-66	34	3	Sub-orbital CSM reentry
Saturn IB	SA-203	AS-203	5-Jul-66	37B	3	Orbit of second stage
Saturn IB	SA-202	AS-202	25-Aug-66	34	3	Sub-orbital CSM reentry
Saturn V	SA-501	Apollo 4	9-Nov-67	39A	3	Orbit and CSM reentry
Saturn IB	SA-204	Apollo 5	22-Jan-68	37B	3	Orbit of LM
Saturn V	SA-502	Apollo 6	4-Apr-68	39A	3	Orbit and CSM reentry
Saturn IB	SA-205	Apollo 7	11-Oct-68	34	3	Manned orbit and CSM reentry
Saturn V	SA-503	Apollo 8	21-Dec-68	39A	3	Manned lunar orbit
Saturn V	SA-504	Apollo 9	3-Mar-69	39A	3	TD&E, LM maneuvers, EVA
Saturn V	SA-505	Apollo 10	18-May-69	39B	3	Manned partial lunar descent
Saturn V	SA-506	Apollo 11	16-Jul-69	39A	3	Manned lunar landing, EVA
Saturn V	SA-507	Apollo 12	14-Nov-69	39A	3	Manned lunar landing, EVA
Saturn V	SA-508	Apollo 13	11-Apr-70	39A	3	Shortened to translunar return
Saturn V	SA-509	Apollo 14	31-Jan-71	39A	3	Manned lunar landing, EVA
Saturn V	SA-510	Apollo 15	26-Jul-71	39A	3	Manned lunar landing, EVA
Saturn V	SA-511	Apollo 16	16-Apr-72	39A	3	Manned lunar landing, EVA
Saturn V	SA-512	Apollo 17	7-Dec-72	39A	3	Manned lunar landing, EVA
Saturn V	SA-513	Skylab 1	14-May-73	39A	3	Skylab orbit
Saturn IB	SA-206	Skylab 2	25-May-73	39B	3	Skylab crew delivery
Saturn IB	SA-207	Skylab 3	28-Jul-73	39B	3	Skylab crew delivery
Saturn IB	SA-208	Skylab 4	16-Nov-73	39B	3	Skylab crew delivery
Saturn IB	SA-210	ASTP	15-Jul-75	39B	3	Apollo-Soyuz rendezvous

called PGM, and was used only on SA-6 and SA-7.

An improved scheme, IGM, was first tested on SA-9, refined on SA-8 and SA-10, and used on all subsequent Saturn launches. Derivation of IGM steering equations began with simplifying assumptions of a flat Earth and constant gravity field. This allowed an analytical solution to the guidance equations, which could be evaluated onboard. By iterative use of this solution (once a second), a highly accurate approximation to an optimum (minimum fuel consumption) trajectory could be achieved.

The advantages of IGM over Polynomial Guidance[48] were:

1. Reduced preflight computation. The number of trajectories considered was reduced by two orders of magnitude.[49] This afforded another advantage:

2. Greater flexibility. Fewer preflight calculations could be performed more quickly, allowing easier adjustment to changed mission conditions.

3. Greater accuracy and hence improved fuel economy.

Conclusion

Saturn I was followed by the Saturn IB and Saturn V programs, which used the knowledge gained by the Saturn I program and some of the components. A new instrument unit, the third version of that stage, was built by the IBM Federal Systems Division in Huntsville for Saturn IB and V. Version 3 was considerably larg-

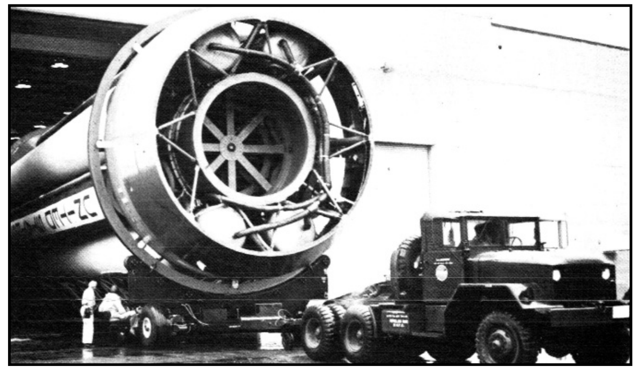


Figure 17. Guidance components were carried in four pressurized canisters stowed in the forward part of the S-I first stage for Saturn I Block I.[52]

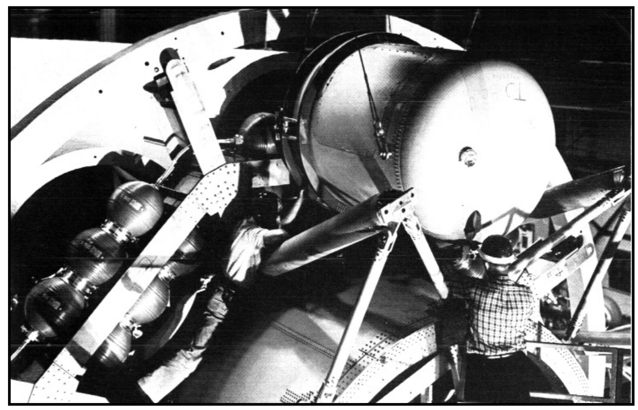
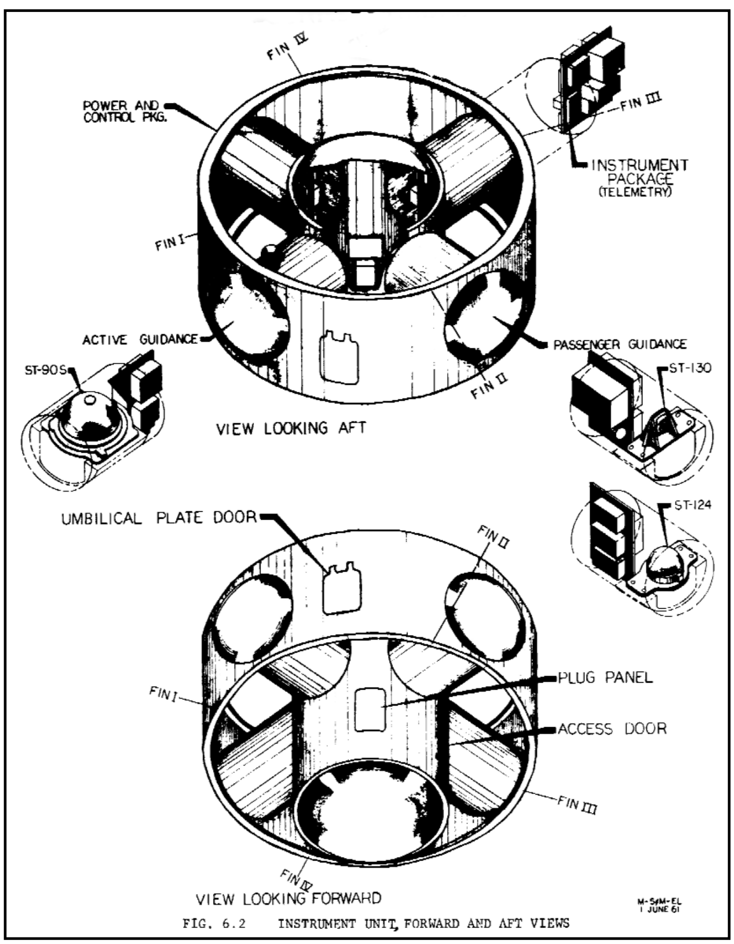


Figure 18. Canisters are installed on the S-I. [53]



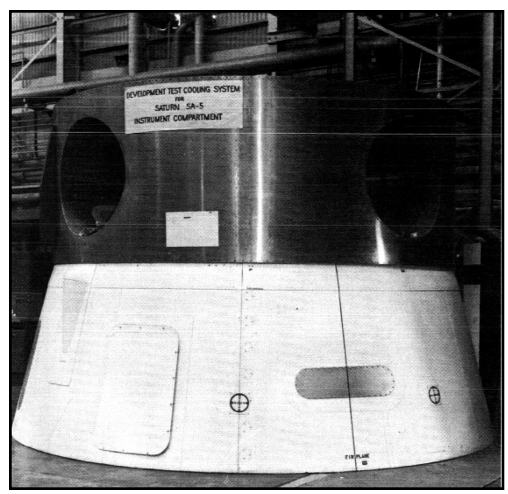


Figure 19. [above]
Mockup of version 1 of the Instrument Unit, to be flown on SA-5.A separate stage, the Instrument Unit, carried Block II guidance components. The cylinder was 154 inches in diameter and 58 inches high, and was both designed and built by NASA Marshall Space Flight Center (MSFC).[54]

Figure 20. [left]
Exploded view of version 1 of the Instrument Unit, with components in pressurized tubes.[55]

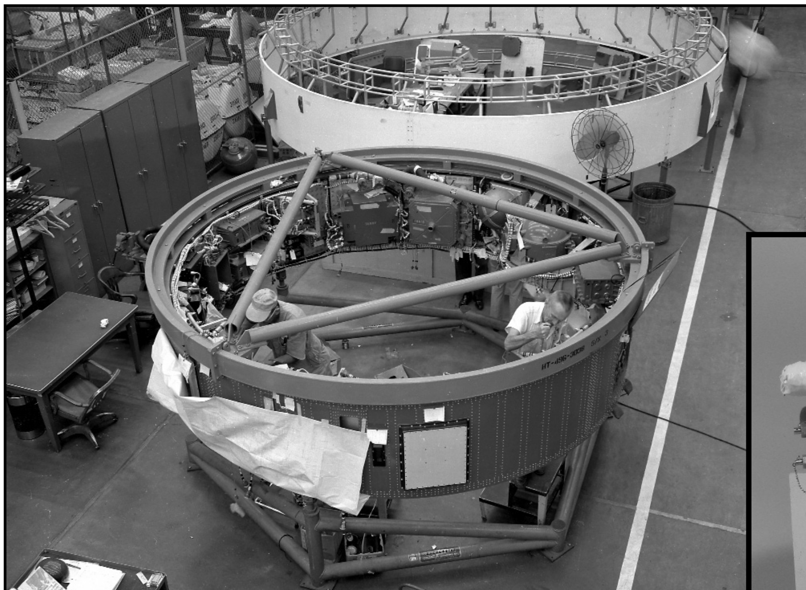


Figure 21. Version 2 of the Instrument Unit in the foreground and Version 3 behind.[56] Version 2, carried by SA-8, -9, and -10, was 154 inches in diameter and 34 inches high. Version 3 flew on Saturn IB and V and was 260 inches in diameter and 36 inches tall.

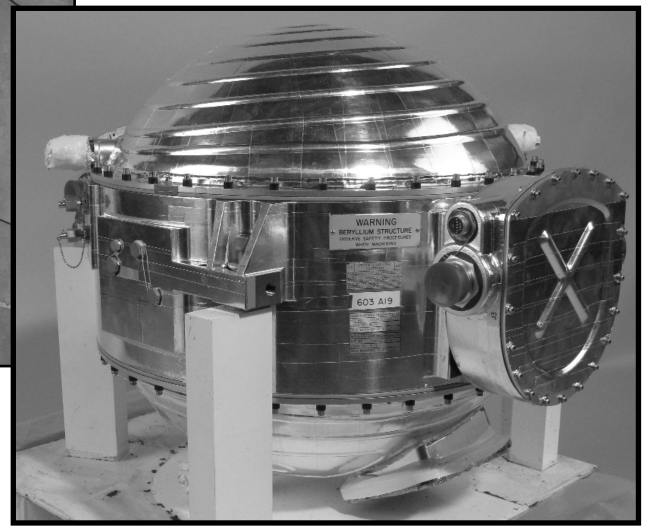


Figure 22. ST-124 in the collection of the National Air and Space Museum.[57] This ST-124 was last modified in April 1974, and may have been manufactured for a mission (*Apollo 18* or *19*) that was canceled. A temperature-controlled, methanol-water mixture flowing through coils on the top and bottom covers held the temperature of the ST-124 constant. A window, facing down to the right, allowed alignment of the inner gimbal by an external theodolite before launch.

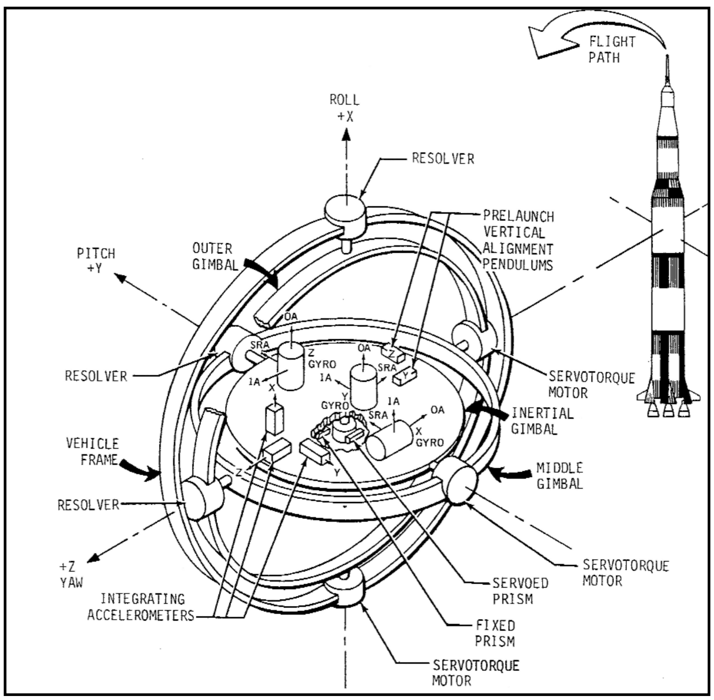


Figure 23. Inertial Coordinate System within the ST-124 Stabilized Platform.[58] Three gyros on the inner gimbal sense any rotations and send signals to circuits outside the ST-124 that generate commands for the servotorque motors that exactly counter the rotations, stabilizing the inner gimbal in a fixed orientation. The integrating accelerometers thus measure vehicle velocity in a fixed (inertial) coordinate system.

er in diameter than version 2 (260 inches versus 154 inches) but only slightly taller (36 inches versus 34 inches). While Version 3 carried the ST-124 stabilized platform that flew on Saturn I, the ASC-15 guidance computer was replaced by the new Launch Vehicle Digital Computer (LVDC), also made by IBM. The flight control computer, manufactured by Electronic Communications, Inc., of St. Petersburg, Florida, had been a box[50] on Saturn I, but for Saturn IB and V it was a large cylinder.

About the Author

Edgar Durbin is a physicist who, since retirement from government service in 2002, has worked part time at the Smithsonian Institution National Air and Space Museum, Department of Space History. Most of his research there has been on navigation, control, and guidance systems used in the Saturn program. 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.

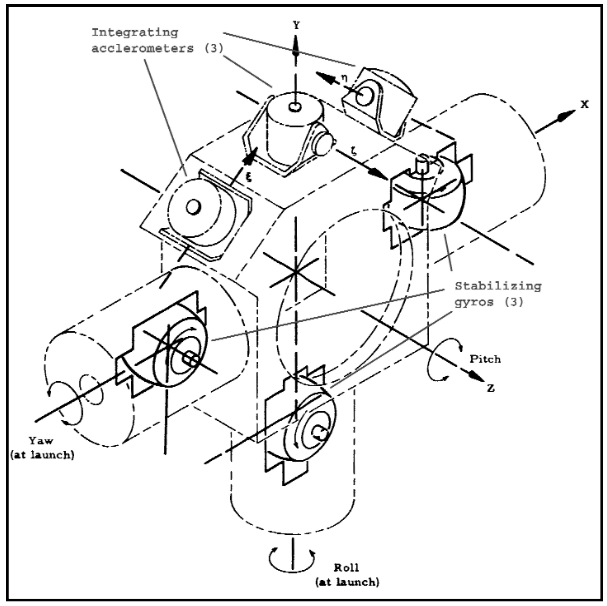
Notes

1. "Proposal: A National Integrated Missile and Space Vehicle Development Program," Army Ballistic Missile Agency, Development Operations Division, Huntsville, Alabama, 10 December 1957. Report No. D-R-37.

2. Roy Johnson, "ARPA Order No. 14-59," Advanced Research Projects Agency, 15 August 1958.

3. Helen T. Wells, Susan H. Whitely, and Carrie E. Karegeannes, *Origins of NASA Names* (NASA Scientific and Technical Information Office, 1976), NASA SP-4402, 17.

Figure 24.(right) Inertial Coordinate Systems within the ST-90 Stabilized Platform.[59] In the ST-90 the accelerometers on the stabilized platform measured accelerations in the ξ, η, ζ system, which was rotated by an angle ε with respect to the X, Y, Z system. For SA-1 ε = 41 degrees.[60] In the ST-124 the accelerometers measured accelerations in the same X, Y, Z system as the stabilized platform. The gimbal system in the ST-124 was "external." That is, the outermost gimbal was attached to the vehicle. In the ST-90 the innermost gimbal was attached to the vehicle, an arrangement called "internal."[61]



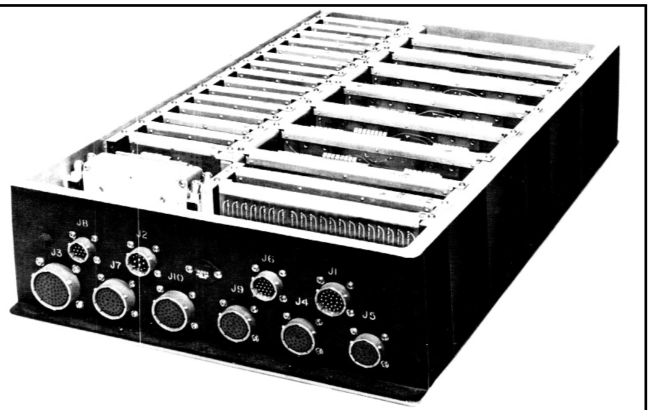


Figure 25. Saturn I flight control computer.[62]

4. The last Saturn vehicle to be launched was AS-210, on 15 July 1975.

5. David S. Akens, *Saturn Illustrated Chronology* (NASA MSFC, 20 January 1971), MHR-5, appendix F, figure 5, "Saturn Engine Applications" with additional data added by the author.

6. For translunar injection, the S-IVB third stage was reignited to increase spacecraft velocity to change its orbit around Earth from approximately circular to highly elliptical. The timing and length of the burn was such as to put the spacecraft at apogee near the Moon. Wikipedia, "Trans Lunar Injection." W. David Woods. *How Apollo Flew to the Moon* (Springer, 2007), chapter 4, "Earth Orbit and TLI."

7. Akens, "Configurations of Saturn Flight Vehicles," *Saturn Illustrated Chronology*, figure 49.

8. Saturn Flight Evaluation Working Group, "Saturn SA-1 Flight Evaluation," NASA MSFC, 14 December 1961, MPR-SAT-WF-61-8, 217.

9. B. E. Duran, "Saturn I/IB Launch Vehicle Operational Status and Experience," paper given at Aeronautic and Space Engineering and Manufacturing Meeting of the Society of Automotive Engineers, Los Angeles, California, 7–11 October, 1968, 3.

10. F. W. Brandner, "Technical Information Summary Concerning Saturn Vehicle SA 2," NASA MSFC, memo dated 5 April 1962, TMX 51831, figure 5 with some lines and text cleaned up for legibility.

11. Saturn Flight Evaluation Working Group, "Results of the Third Saturn I Launch Vehicle Test Flight SA 3," NASA MSFC, 26 February 1964, MSFC MPR-SAT-65-13, 21.

12. Saturn Flight Evaluation Working Group, "Results of the Sixth Saturn I Launch Vehicle Test Flight (SA 6)," NASA MSFC, 1 October 1964, MPR-SAT-FE-64-18, figure 7-1.

13. Saturn Flight Evaluation Working Group, "Results of the Seventh Saturn I Launch Vehicle Test Flight (SA 7)," NASA MSFC, 30 December 1964, MPR-SAT-FE-64-19, figure 7-1.

14. "Saturn I Electrical Power and Systems Integration SA 8 through SA 10," NASA MSFC, 5 February 1965, NASA TM X-53205, figure 3, 9.

15. Walter Haeussermann, F. Brooks Moore, and Gilbert G. Gassaway, "Guidance and Control Systems for Space Carrier Vehicles," *Astronautical Engineering and Science from Peenemünde to Planetary Space. Honoring the Fiftieth Birthday of Wernher von Braun* (McGraw-Hill, 1963), 166.

16. Ernst D. Geissler and Walter Haeussermann, "Saturn Guidance and Control," American Rocket Society, *Astronautics* (February 1962):44, 88.

17. "Results of the Third Saturn I," 26: "Statham type control accelerometers will be flown in 'closed loop' control on SA-4, in place of the local angle-of-attack transducers."

18. H. J. Weichel, "SA 8 Flight Test Data Report," NASA MSFC, 2 August 1965, NASA TM X-53308, 8. "Saturn SA 2 Flight Evaluation," NASA MSFC, 5 June 1962, MPR-SAT-WF-62-5, 106.

19. Figure in "Saturn SA-2 Flight Evaluation," 297. Description on page 106.

20. "The Apollo 'A'/Saturn C-1 Launch Vehicle System," NASA MSFC, Saturn Systems Office, 17 July 1961, NASA TM X-69174, MOR-M-SAT-61-5, 227. Brandner, "Saturn Vehicle SA-2," figure 6. There are actually three equations, one each for pitch, yaw, and roll.

21. Brandner, "Saturn Vehicle SA-2," 2.

22. John M. Caudle and Donald C. Colbert, "Flight Control Computer for Saturn Space Vehicles," *IEEE New Links to New Worlds, 1963 National Space Electronics Symposium*, figure 4. Walter Haeussermann, "Description and Performance of the Saturn Launch Vehicle's Navigation, Guidance, and Control System." NASA MSFC, Huntsville, Alabama, July 1970, NASA TN D-5869, 10.

23. "Apollo A/Saturn C-1," section 14, "Control Dynamics."

24. "Apollo A/Saturn C-1," 227. "Results of the Third Saturn I," 23. "Results of the Fifth Saturn I," 1.

25. Caudle and Colbert, "Flight Control Computer," 267.

26. F. Brooks Moore and Melvin Brooks,

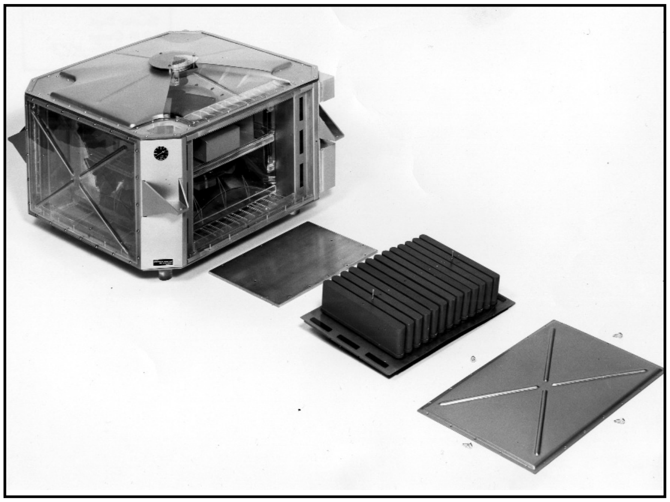


Figure 26. ASC-15 digital guidance computer.[63] This computer was used on Titan II and later adapted by NASA for use as the guidance computer on Saturn I Block II. One of the four side panels is removed, revealing 13 of the 52 logic sticks. The port in the middle of the top is for cooling air. “The outer frame consists of four aluminum corner posts which are welded to, and separated by, a series of aluminum rails to form a boxlike structure. Four identical side covers, plus a bottom and top cover, constitute the external appearance of the MGC [Missile Guidance Computer, or ASC-15]. All covers are formed from laminated plastic, covered with gold-plated aluminum foil. The covers are convex and are formed with stiffening ridges for extra support. The plated foil on each cover provides radio interference shielding. This, in turn, is covered with a protective plastic covering. The four side covers support a total of fifty-two logic sticks, each containing four welded encapsulated modules [WEM], consisting of resistor, transistors, capacitors, relays, etc. These logic sticks contain the logic circuitry of the MGC and are encased inside the side covers of the MGC.”[64]

“Saturn Ascending Phase Guidance and Control Techniques,” *Technology of Lunar Exploration* (Academic Press, 1962), 18–209. Figure 8 is on page 206.

27. Rudolf Decher, “The Astrionics System of Saturn Launch Vehicles,” NASA MSFC, Huntsville, Alabama, 1 February 1966, NASA TM X-53384, 35.

28. Brandner, “Saturn Vehicle SA-2,” fig 6.

29. “Saturn SA-2 Flight Evaluation,” 32, fig 4–6.

30. “Saturn SA-2 Flight Evaluation,” 85.

31. “Astrionics System Handbook Saturn Launch Vehicles,” NASA MSFC, 1 November 1968, MSFC No. IV-4-401-1, IBM No. 68-966-0002, 3.3–5.

32. Page 1.3–1 of “Astrionics System Handbook”: “Guidance of the vehicle throughout the first stage burn is achieved through a preset time-tilt (pitch) program.”

33. Brandner, “Saturn Vehicle SA-2,” 2.

34. Brandner, “Saturn Vehicle SA-2,” figure 7. See also Saturn SA-2 Flight Evaluation, figure 6–16.

35. “Project Apollo Coordinate System Standards,” NASA SE 008-001-1, June 1965. Figure A-8a, “Saturn I and IB Launch Vehicle Structural Body Axes.”

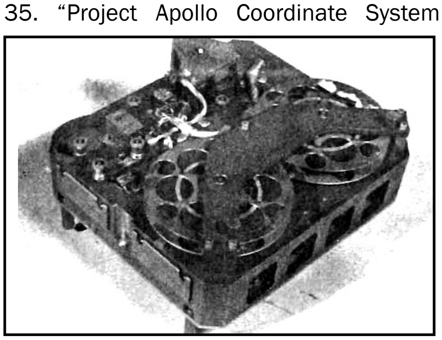


Figure 27. Saturn I program device.[65] This multitrack precision tape player was used on both Jupiter and Saturn I to determine the sequence of certain time-dependent events. 13 inches by 11 inches by 7.5 inches.

36. Brandner, “Saturn Vehicle SA-2,” fig 6.

37. Caudle and Colbert, “Flight Control Computer,” 1.

38. A tracing of Brandner, “Saturn Vehicle SA-2,” figure 3

39. Decher, “Astrionics System of Saturn,” 25.

40. Saturn Flight Evaluation Working Group, “Results of the Fifth Saturn I Launch Vehicle Test Flight (SA 5),” NASA MSFC, 22 September 1964, MPR-SAT-FE-64-17, 48.

41. A. A. Conway and H. K. Bennett, “Saturn I Electrical Power and Systems Integration SA 5 through SA 7,” NASA MSFC, Astrionics Division Electrical Systems Integration Branch, 25 March 1963, MTP-ASTR-E-63-5, 7: “The control of inflight sequential events after liftoff is derived from the program device on SA-5 and SA-6. On SA-7, the control of sequential events will be derived from the guidance computer. One channel of the program device delivers the pulses to the flight sequencer.”

42. Brandner, “Saturn Vehicle SA-2,” figure 7: “Tilt program must be selected about one month before launch because a change in program requires a new cam.”

43. R. A. Chapman, “Saturn I Block II Guidance Summary Report,” NASA MSFC, 23 February 1966, NASA TM X-53398. On page 3 he makes the distinction between guidance for SA-7 and succeeding missions. The PGM is explicitly described by Walter Haeussermann, “Guidance and Control of Saturn Launch Vehicles,” AIAA, Second Annual Meeting, San Francisco, California, 26–29 July 1965, paper 65-304.

44. “Open loop” connotes a feedback loop that is not closed. Changing to active guidance was not accomplished by closing a switch, but by loading a new program in the guidance computer that changed the algorithm by which the desired heading was calculated. In open loop the heading was calculated by a polynomial that was a function only of time. In active guidance, the heading calculation took account of vehicle position, velocity and acceleration, which were the results of the preceding heading commands plus the influences of atmospheric forces and vehicle dynamics.

45. Active guidance started for SA-6 at 168.23 seconds after launch; for SA-7 at 165.67 seconds, for SA-8 at 166.69 seconds, and for SA-10 at 168 seconds. See flight evaluation reports for each mission.

46. Adapted from Table 2.2–1 in Haeussermann, “Guidance and Control of Saturn Launch Vehicles,” AIAA Paper 65-304.

47. David H. Schmieder and John B. Winch, “Adaptive Guidance,” *Papers Presented at Session K of the NASA-University Conference on the Science and Technology of Space Exploration*, Chicago, Illinois, 1–3 November 1962. NASA-SP-17.

48. Walter Haeussermann and Robert Clifton Duncan, “Launch Vehicle Inertial Navigation and Guidance,” *Status of Guidance and Control Methods, Instrumentation, and Techniques as Applied in the Apollo Project* (NASA, 1964), chapter 2. 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, Düsseldorf, Germany, 21–22 October 1964.

49. Haeussermann in AIAA paper 65-304 says for PGM “approximately 100 trajectories are required.” Also, “The PGM scheme requires approximately 100 to 300 precalcu-

Figure 28. [Above] Flight sequencer (bottom) and slave (top).[66] "The flight sequencer is a relay device that functions as a step switch to program distribution of 28 V d.c. power to relays and other control actuation devices. The basic Saturn flight sequencer provides 10 steps, or distribution points, for control functions. The basic unit can be connected to one or more slave units to increase the number of steps in multiples of ten. For Saturn use, the flight sequencer is used with a single slave unit to provide 20 steps or distribution points. Physically, the flight sequencer consists of relays, diodes, and two printed circuit boards."

Figure 29. [right] Flight sequences for SA-5, controlled by two tracks of the program device.[67]

PRELIMINARY SA-5 S-I PROGRAM

Step	Flight Time From Liftoff	Function
1	LO+2	Spare
2	LO+10	Energize engine-out time relay
3	LO+21	Spare
4	LO+30	Spare
5	LO+39	Close fuel press valve No. 3; start recorder
6	LO+54	Close fuel press valve No. 2; start camera lens purge
7	LO+70	Close fuel press valve No. 1; energize LOX-SOX high pressure valves Nos. 1 and 2
8	LO+85	Spare
9	LO+102	S-IV telemetry calibrate command
10	LO+113	LH_2 prestart; power to 6 cameras
11	LO+125	Power to charge port vent EBW
12	LO+132	Enable propellant level sensors
13	LO+140.0	Inboard cutoff; open LOX-SOX purge valves Nos. 2, 3, 5, and 6
14	LO+142	Spare
15	LO+142.8	Open LOX-SOX purge valve No. 4
16	LO+143.4	Spare
17	LO+143.9	Open LOX-SOX purge valves Nos. 1 and 7
18	LO+146	Outboard engine cutoff
19	LO+146.2	Spare
20	LO+146.6	Separation - signal to separation EBW firing unit and retrorocket EBW firing units. Start 25 second delay timer for camera ejection and tape recorder playback

PRELIMINARY SA-5 IU PROGRAM

Step	Flight Time From Liftoff	Function
1	LO+5	Extended roll on
2	LO+20	Extended roll off
3	LO+30	Switch point control computer
4	LO+60	Switch point control computer
5	LO+90	Switch point control computer
6	LO+134.4	Stop program device
7	LO+146.289	Fire ullage rockets
8	LO+146.4	Switch control system to S-IV stage; S-I/S-IV stage separation
9	LO+147.8	Activate He heaters LOX valve
10	LO+148.1	S-IV engine start
11	LO+151.0	Enable S-IV engine-out
12	LO+152.0	Spare
13	LO+153.0	Enable S-IV propellant utilization
14	LO+166.4	Jettison ullage rockets
15	LO+450.4	Tape recorder record
16	LO+510	Switch point control computer
17	LO+598.4	Arm S-IV engine cutoff
18	LO+603.4	S-IV engine cutoff
19	LO+632.4	Tape recorder stop
20	LO+635.4	S-IV telemeter calibration and tape recorder playback

lated trajectories, whereas only one or two precalculated trajectories are required to provide the presetting for the IGM scheme." Haeussermann and Duncan, "Status of Guidance" says "The number of precalculated trajectories required to generate the guidance equations varies from as few as one or two to as many as 300. The minimum propellant polynomials require the largest number; the schemes employing a standard reference trajectory or a set of explicit equations need the smallest number. Polynomials designed primarily for accuracy and not for the minimum propellant consumption may require from 25 to 50 trajectories."

50. Caudle and Colbert, "Flight Control Computer," figure 10, gives no dimensions or weights. Haeussermann, Moore, and Gassaway, "Guidance and Control Systems," 175, says "The control computer used in the early Saturn C-l vehicles [that is Saturn I] had a volume of 0.5 ft^3, a weight of 30 lb, and a power requirement of 150 watts. As presently visualized, the Saturn C-5 class control computer will have no major functional differences from those previously described." "MSFC Artifacts Catalog" shows a "computer used on the first flour flights of SATURN I" that is 24 inches by 12 1/8 inches x 12 inches [that is 2.0 ft^3] and weighs 55 pounds.

51. "Saturn I Summary." NASA MSFC, 15 February 1966, http://hdl.handle.net/2060/1966 0014308. Courtney G. Brooks, James M. Grimwood, and Loyd S. Swenson, *Chariots for Apollo: A History of Manned Lunar Spacecraft*. NASA History Series, SP-4205, 1979.

52. "Steps to Saturn," NASA MSFC, 29. http://hdl.handle.net/2060/19660083255 .

53. "Steps to Saturn," 29.

54. "Steps to Saturn," 66.

55. "ApolloA/Saturn C-1," figure 6.2, 133.

56. NASA MSFC Image Exchange (MIX). http://mix.msfc.nasa.gov/IMAGES/HIGH/6412716.jpg.

57. Photograph taken by Edgar Durbin at NASM Garber Facility, 4 February 2010.

58. "Saturn V Flight Manual SA-507," MSFC-MAN-507, 15 August 1969, figure 7-16, 7–18.

59. R. A. Chapman, "A Method of Determining the Source of Errors in Guidance Measurements and the Resultant Errors in Earth-Fixed Components," NASA MSFC, MTP-AERO-62-76, 22 October 1962, figure 1, 12.

60. "Saturn SA-1 Flight Evaluation," 106.

61. F. K. Mueller, "The New Look in Gimbal Systems," *Missiles and Rockets* (March 1958): 199–200.

62. Caudle and Colbert, "Flight Control Computer," figure 10.

63. Photo provided by Stacy L. Fortner, associate archivist, IBM Corporate Archives, Somers, New York.

64. "Missile Launch/Missile Officer (LGM-25) Missile Systems," USAF, Sheppard Technical Training Center, May 1967, Student Study Guide OBR1821F/3121f-V-1 through 4, Volume I of II, 62. Excerpt provided by Titan Missile Museum, Sahuarita, Arizona.

65. "MSFC Artifacts Catalogue," NASA MSFC Management Services Office, 1 July 1976, 206.

66. Conway and Bennett, "SA-5 through SA-7," 38–40.

67. Conway and Bennett, "SA-5 through SA-7," 12.