# Manual control of the Mercury spacecraft

**The Astronaut will manually control Mercury as a normal part of his flight program and may explore his capabilities in manual control of spacecraft through several critical maneuvers**

By *Robert B.* Voas

NASA MANNED SPACECRAFT CENTER

**Robert B. Voas is Astronaut Training Officer for the NASA Space Task Group, and has played an important role in the design and development of simulators for the Mercury program. Dr. Voas received a Ph.D. in psychology in 1953 from the Univ. of California at Los Angeles. After serving with the Navy at the School of Aviation Medicine, Pensacola, Fla., where he was involved in research on selection and training of pilots, he joined the Space Task Group in October 1958 and assisted the Project Mercury management in the selection of the Astronauts. During the past two years, Dr. Voas has been coordinating the program which has brought the seven Mercury Astronauts to a high level of proficiency, and is presently concerned with the program to maintain this high level of proficiency throughout the period of Mercury manned flights.**

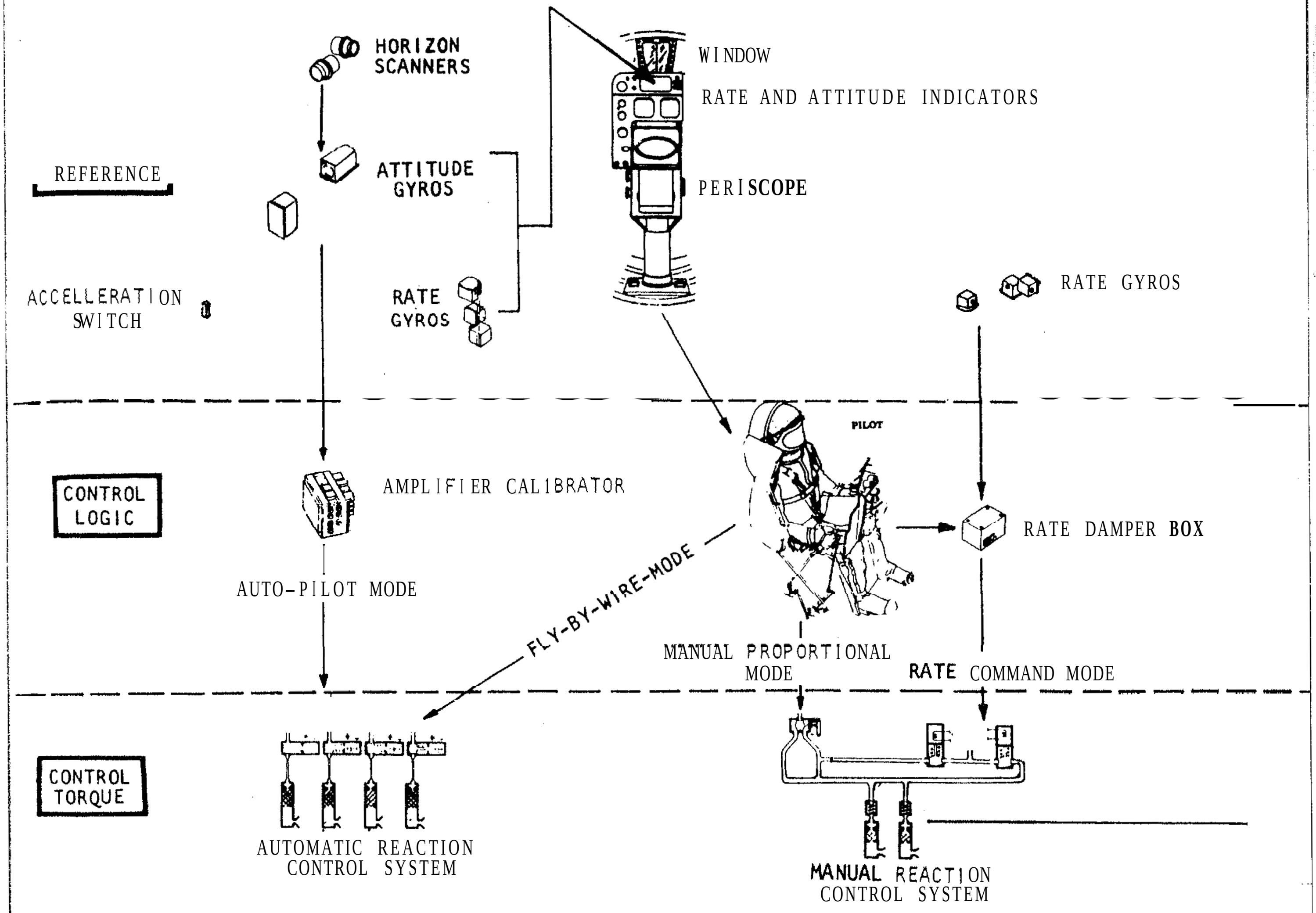
THE Mercury flight begins and ends with periods during which the Astronaut does not control the vehicle's attitude and flight path. During the launch, trajectory and attitude control come from the booster guidance system and the ground control center. Landing occurs passively by means of parachutes.

The lack of manual control during these two phases of the mission has led to an underestimation of the Astronaut's role in controlling the attitude of the Mercury spacecraft, It should be remembered that the pilot may elect to take full control over the attitude of the vehicle any time from separation of the booster through orbital flight, retrofire, and re-entry. During this period, there are four tasks which face the Astronaut: Control of attitude in orbit, control of attitude during retrofire, rate damping during re-entry, and recovery from tumbling maneuvers.

Control of attitude in orbit involves bringing the vehicle to a desired attitude in reference to the earth. The normal flight attitude for the capsule is –34 deg pitch (small end pointed down) and 0 deg roll and yaw. Should he wish to vary this attitude, the Astronaut can usually make the maneuver in a single axis at a time. Varying attitude in orbit is relatively simple if high tolerances in holding a given attitude are not required. Such a maneuver is relatively easy because it can be done a single axis at a time and because time is usually not a critical factor. The primary problem in learning to do maneuvers effectively is to control so as to use a minimum amount of fuel.

The most critical maneuver for the Mercury Astronaut is controlling the vehicle during retrorocket firing. Three retrorockets are ignited 5 sec apart and burn for 12 sec each, producing a variable deceleration pattern during the 22-sec retrofire period. Due to uncertainties in the center of gravity and retrorocket alignment, torques about the major axes of the vehicle may be produced. These torques are difficult to estimate, but it is expected that 95% of the time they will not exceed two-thirds of the control thrust available. Since high torques are developed and they are variable through the 22-sec period of retrofire, rapid and accurate responses are required to keep the vehicle under control.

## Control Systems in the Project Mercury Spacecraft



## Summary of Project Mercury Trainers in Attitude Control

| Trainer | Control Modes | | | | Reference Systems | | | | Types of Tasks | | | | Environmental Conditions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Manual Proportional | Fly-By-Wire | Rate Command | Mixed | Instruments | Window | Periscope | Mixed | Orbit Attitude Control | Retrofire | Reentry Rate Damping | Recovery From Tumbling Maneuvers | Linear Acceleration | Angular Acceleration | Pressure Suit |
| **Procedures Trainer*** | X | X | X | X | X | | X | X | X | X | X | | | | X |
| **ALFA** | X | X | | | X | X | X | X | X | X | | | | X | |
| **Mastif** | X | | | | X | | | | | | | X | | X | |
| **Centrifuge*** | X | | | | X | | | | X | X | X | | X | | X |

*** Can be used while performing other tasks.**

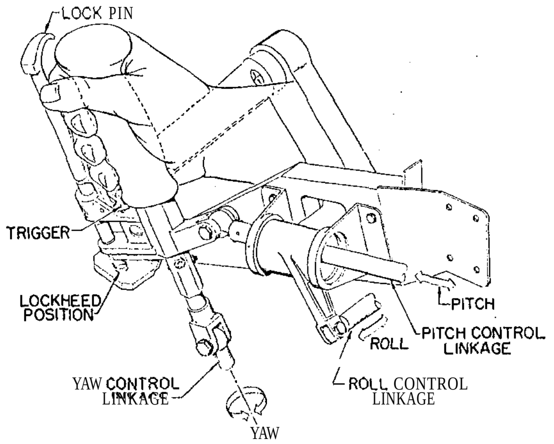
A third task is the damping of oscillations of the Mercury spacecraft during re-entry. It is stable only in the blunt-end-forward attitude during the re-entry, and oscillations about the basic front-end-forward position occur unless it is perfectly aligned throughout re-entry. The Astronaut's task is to damp out these oscillations. Since the frequency and amplitude of the oscillation vary throughout re-entry, re-entry rate damping could be a difficult task on a vehicle with low stability. However, wind-tunnel data and flight experience to date indicate that the re-entry stability of the Mercury spacecraft is high, perhaps high enough to re-enter successfully without a control system. Training experience has indicated that, at levels of stability demonstrated by the spacecraft, the damping of oscillations is a relatively simple task for the pilot.

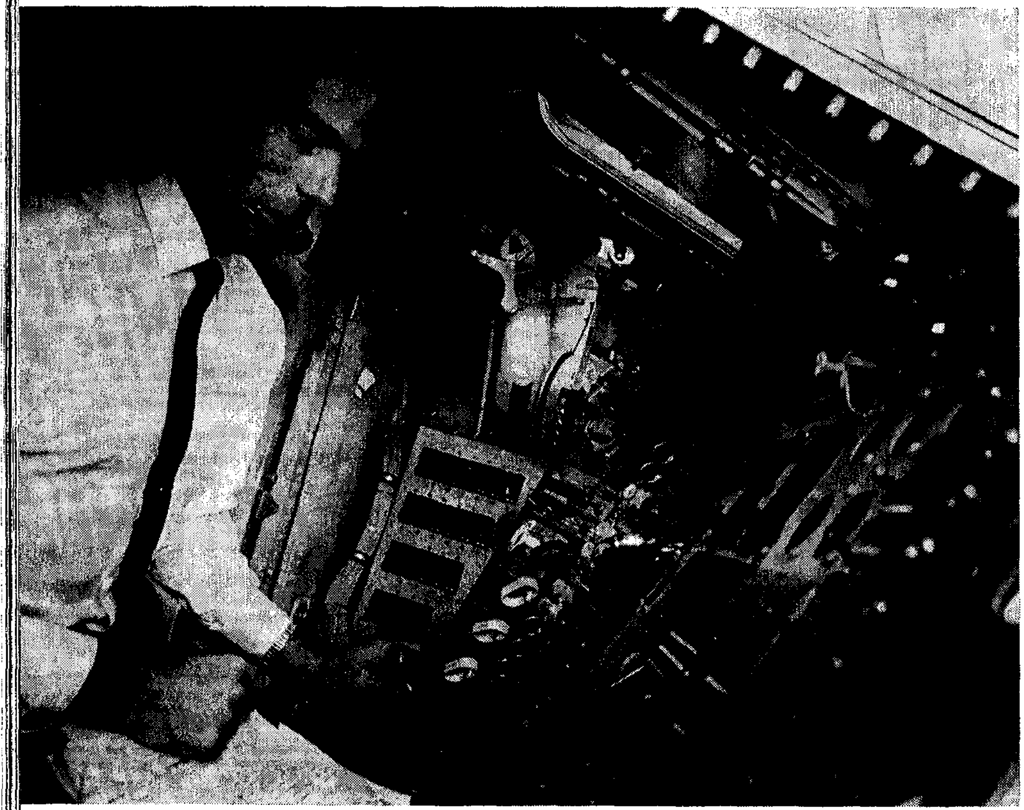
Finally, the Astronaut must be able to recover from a tumbling maneuver. Tumbling of the Mercury vehicle is very unlikely, but it could result from unusual torques produced by separation from the booster or by one of the reaction control jets freezing in an open position. In the event of tumbling, the Astronaut must first bring the vehicle to a stationary position, reorient to the earth, and then cage and reset his attitude gyros to restore his instrument attitude reference.

To accomplish these four functions, the Astronaut has available to him a complex but flexible control system, described by Senders and Lindquist in "Early Development of a Vehicle Attitude Display and Control" (ARS Preprint 1400-60). This system gives alternative modes of flight control, described by the illustration on page 19. There are two completely independent control systems—an automatic system, having a pair of high- and a pair of low-torque reaction jets for each axis, and a manual system with a single set of proportional reaction jets. Each of these systems has its own fuel supply and controls so that they are completely redundant.

(CONTINUED ON PAGE 34)

## Three-Axis Side-Arm Controller





**Mercury Astronaut M. Scott Carpenter operates controls inside Procedures Trainer. Note the window just above his eye level. The view through the window can be used as a reference in manual control of the spacecraft.**

## Mercury Spacecraft

(CONTINUED FROM PAGE *20*)

When the Astronaut wishes to exercise manual control—and he will as a normal part of all flights—he has access to both control systems. He can fly through the automatic control system, using the "fly-by-wire" mode of manual control. In this mode, he has an on-off control over the high- and low-torque jets of the automatic control system. A deviation of the control stick one quarter of the full throw turns on the low-torque jets, and three-fourths of the full throw actuates the high-torque jets.

In addition to this access to the automatic control system, the **Astronaut** may use two modes of control through the manual-control-system jets. The first of these, the "Manual Proportional" mode, makes use of a set of mechanical linkages to open valves on the reaction jets by an amount proportional to the deviation of the stick. A second control system making use of the manual jets is the "Rate Command" mode. In this mode, electrical outputs from the potentiometer attached to the stick are fed into a logic system which receives information from its own set of rate gyros. Through this system, signals are sent to the manual-control-system solenoid valves; this gives a capsule rate proportional to the deviation of the hand controller.

Thus, the pilot has available to him three major manual control systems: An on-off, fly-by-wire mode operating through the automatic control jets; a proportional acceleration control mode; and a proportional rate control mode operating through the manual reaction jets.

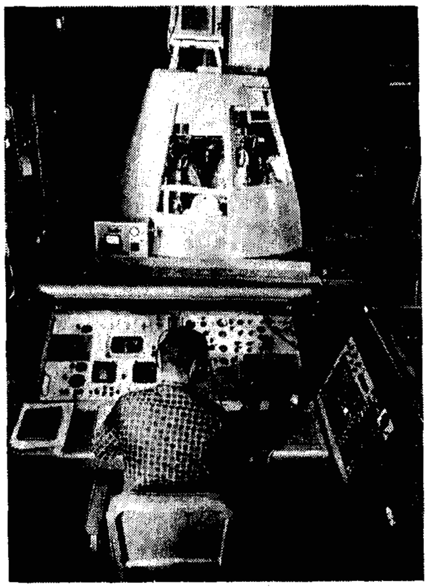
More than one of these systems can be used at a time. Since the automatic reaction jets and the manual reaction jets are completely independent, it is possible for the pilot to exercise control through the manual jets while the autopilot is exercising control through the automatic jets. One occasion for use of both control systems would be in maneuvering in orbit when the Astronaut desires to let the autopilot control two axes, such as roll and pitch, while he takes control in yaw. This manual control in a single axis **is** possible through a set of valves which cut off the automatic reaction jets a single axis at a time, thus providing a number of possible combinations of automatic and manual control.

In addition to the possibility of combining manual and autopilot control, it is also possible *to* use the fly-by-wire with either the manual-proportional or rate-command mode. In this way, the Astronaut can achieve double authority for difficult retrofire problems. All three manual control systems, whether operated singly or in combinations, are operated through the single, right-hand side-arm controller, shown on page ***20.*** This is a three-dimensional controller giving pitch thrust by a fore or aft movement, roll thrust by a side-to-side movement, and yaw thrust by a twisting movement.

The Astronaut has available to him three major attitude reference systems. His primary display consists of a **LABS** indicator, modified to show rates about the three capsule axes. Capsule attitude is displayed on three separate indicators, placed around the rate indicator, on the panel directly opposite the Astronaut's head. This display system was developed on the basis of simulation studies which indicated that the well-trained pilot primarily used rate information to control the retrofire.

### External References Used

Two systems of external reference are available to the Astronaut. The first of these is the periscope, which gives him a nadir view of the earth below the capsule. Through the periscope, the earth appears as a ball that can be centered by reference lines to determine the earth vertical. This provides a good reference in pitch and roll. Yaw, or heading angle, must be determined by the drift of terrain **across** the face **of** the scope. This is a more difficult problem, since a pattern of clouds or terrain must be visible below the vehicle. At night, over unpatterned cloud cover, or over the oceans when no clouds are present, drift may be difficult to determine. Furthermore, small rates in pitch and roll can confuse the determination of yaw, since they produce apparent drift. Despite these problems, it appears likely that fairly frequent checks of yaw will be possible.



This fixed-base Procedures Trainer allows the Astronaut to practice **attitude**-control problems and emergency procedures for a Mercury flight. Con**trol** problems and system errors can **be** inserted **into** the trainer from the instructor's console **in** the foreground, and the instructor can watch Astronaut responses on the console's panel.

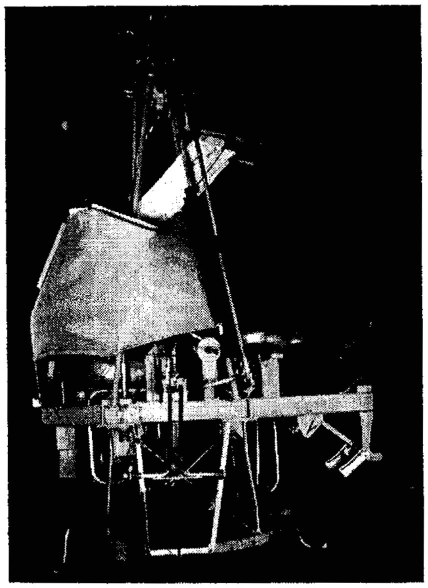
The yaw-reference problem has two aspects: The initial heading determination using terrain drift, and, secondly, the maintenance of yaw position during retrofire, which must be done by observing rotational movements of the earth in the periscope. For this latter purpose, there must be some patterned terrain, such as a coast line, which the Astronaut can use for heading reference. Such a reference may not always be available where the retrofire maneuver must be initiated.

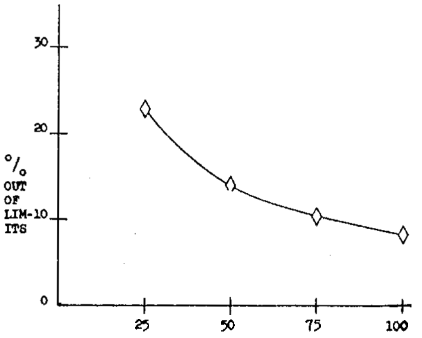
Another problem with the use of the periscope is the unusual view of the earth which it provides. This produces some negative transfer to the control problem. Since the view is perpendicular to, rather than parallel with, the earth's surface, some initial confusion in roll and yaw control with reversals of control have been noted during training. However, with training, such reversals have been eliminated.

**A** second method of external reference is the capsule centerline window. Through this window, the pilot has a view of a small portion of the horizon and the sky. Pitch and roll reference is similar to that of normal aircraft. As with the periscope, drift (in this case, the drift of the stars as well as of the terrain) may be used as a yaw reference. More precise heading reference can be provided by supplying the Astronaut with the heading angles of the major stars which fall within a few degrees either side of the orbital plane. He can then orient the vehicle in yaw within a few degrees whenever a known star appears in the window.

To train the Astronauts to use these Mercury control systems, a number of fixed and moving base simulators have been employed. No single trainer could be provided that simulated all of the control tasks, with all the available control and reference systems, under the required environmental conditions. The table on page 19 outlines the capability of each of the trainers we will describe here.

The Mercury Procedures Trainer, shown at left here, incorporates a complete simulation of the cockpit





Left, the ALFA simulator without the Astronaut aboard; and right, a graph showing the percentage **of** trials **in** which the Astronauts allowed the vehicle ***to* get** outside the retro-attitude limits.

and support for the pressure suit. It permits simulation of both normal operation and malfunctions of the major capsule systems, besides the attitude-control problems, as we have described them. The periscope display is simulated with CRT on which a large circle is generated to simulate the earth for pitch and roll reference. Yaw reference is provided by a small circle which drifts across the display. The external view through the window is not animated.

The manual proportional mode has been emphasized in training the Astronauts, since it is independent of the vehicle electrical systems and represents the ultimate backup. Through extensive practice with this system, the Astronauts have achieved a high level of skill in controlling the spacecraft.

During some of this training, the Astronauts have worn the Mercury full-pressure suit. With this suit inflated to 5-lb over-pressure to simulate a cabin decompression, they have practiced controlling the spacecraft attitude during simulated retrofire. Data from the Procedures Trainer indicate that, while controlling in the pressurized suit is more fatiguing, the Astronauts are able to keep the attitudes within as close tolerances while pressurized as under normal conditions.

In addition to this fixed-base Procedures simulator, three moving-base facilities have been utilized to train the Astronauts in attitude control. The first of these is the Air-Lubricated Free-Attitude Trainer (ALFA), shown on this page, which was designed and developed by Harold I. Johnson of the NASA Manned Spacecraft Center. This trainer moves on an air-bearing and has **360** deg of freedom in roll and **35** deg of freedom in pitch and yaw. The Astronaut operates compressed air jets through a Mercury hand controller. Retrofire disturbance torques can be simulated through special compressed-air jets.

Two attitude-control systems are simulated on ALFA: Manual proportional and fly-by-wire. In the fly-by-wire simulation, only the low-torque jets (used for attitude control in orbit when attempting to minimize fuel consumption) have been mounted on ALFA. All three reference systems are simulated. The periscope is simulated through a bug-eye lens and a system of mirrors which present a view of a circular screen on which a map of the earth is projected from a film strip. The actual Mercury gyro package and instrument display are mounted on the trainer. The window display is simulated only schematically by an illuminated strip to represent the horizon and small bulbs to simulate the stars.

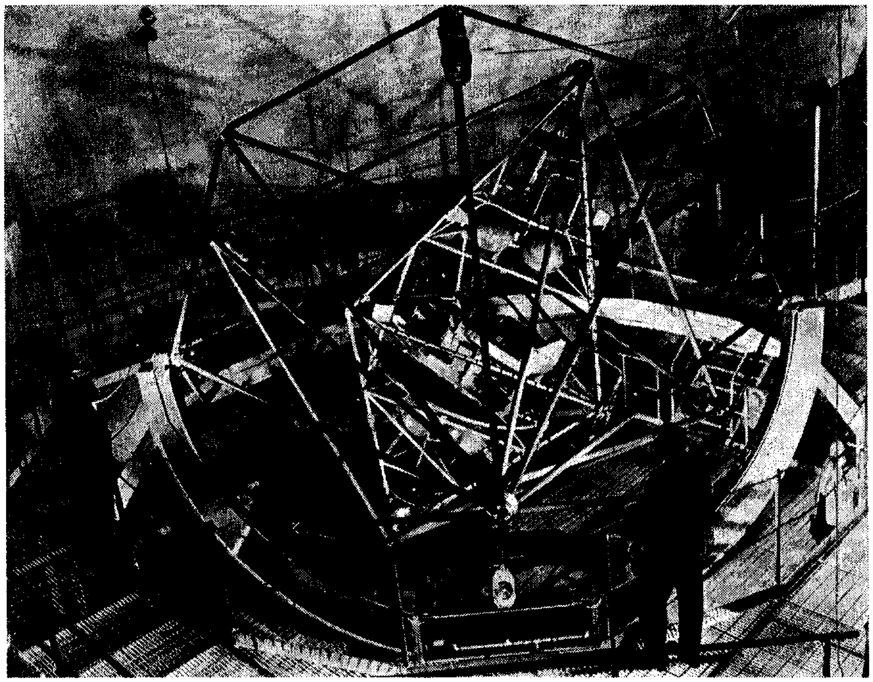
### Retrofire Training

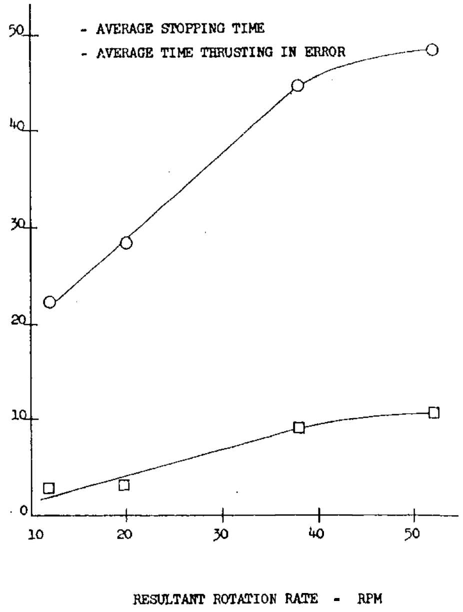
The graph above indicates early progress of training in the retrofire problem using ALFA. It shows the frequency with which the trainer was allowed to get outside, the attitude limits— **30** deg in yaw and roll and ±12 in pitch —during retrofire, **us**ing the periscope reference and the manual proportional control mode. Beyond these limits, retrofire is interrupted until the vehicle attitude is brought back within limits. This graph shows combined results for all Astronauts through the first **100** trials. The frequencies shown are not directly applicable to the actual Mercury flights, since much higher misalignment torques are used during training runs than will be typical of the normal mission. (It is expected that ultimately a criterion will be reached such that less than **5%** of the trials at these high torque levels will result in attitudes outside the permission limits.) This curve demonstrates the difficulty of the task and the relatively long periods of training that are required to produce a high degree of skill.

A second moving-base device used in Astronaut training was the Multi-Axes Test Facility (MASTIF), shown on page **38,** a three-gimballed tumbling simulator at NASA Lewis Research Center. Results of research with this device were described by Useller and Algaranti at the **1960 IAF** meeting in Stockholm. In MASTIF, the Astronaut sits in the cockpit in the center of the gimballed device and is rotated in each of three dimensions at rates up to **30** rpm. Spinning each of the gimbals at **30** rpm simultaneously produces **a** resultant random tumbling rate on the cockpit of approximately 50 rpm. After all three gimbals are moving at the desired rate, control can be turned over to the pilot, who attempts with the use of reaction controls and the Mercury rate indicator to bring the gondola to a stop. The graph on page **38** gives the time required by the Astronauts to stop the movement of the simulator as a function of the resultant rotation rate of the cockpit. As can be seen from this graph, the Astronauts were able to bring the trainer to a stop from a 50-rpm rotation in about ***50*** sec.

The Astronauts performed this maneuver with rate information only. The attitude indicators were not mounted on this trainer, since, if the vehicle were to tumble, the attitude indication would be unreliable. The pilot tended to fight the rotation in only one axis at a time throughout the time the simulator was in motion. The lower line of the graph on page **38** gives the time during which the Astronaut misapplied control thrust, adding to the motion of the vehicle rather than reducing it. Note that this time of thrust error tends to remain a constant fraction of the total time to stop. There is little increase in the percent of control errors with increasing rotation rate within the rotational speeds used.

This exercise on the MASTIF demonstrated the ability of the Astronauts to bring a tumbling vehicle to a stationary position in a relatively short period of time. It also demonstrated the adequacy of the rate indicator for this purpose. While tumbling is a very-low-probability event for the Mercury capsule, it was felt that this training experience was highly desirable as a general confidence builder.





The photo at the left shows the MASTIF simulator at NASA Lewis Research Center, an Astronaut aboard trying his hand at countering roll, pitch, and yaw with the side-arm controller. The graph shows stopping times and errors made by Astronauts in training on MASTIF.

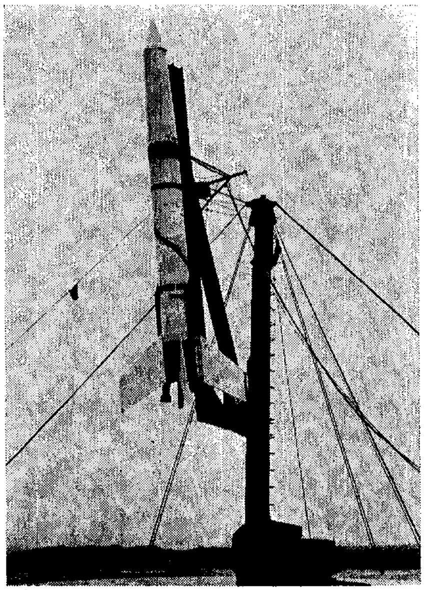
Another moving-base simulator which has been used in the Mercury training program is the Navy's Johnsville centrifuge. This device simulates linear acceleration loads associated with the mission. Two of the four types of control problems discussed previously involve varying levels of linear acceleration. Each retrorocket will produce approximately **0.4** g for the period it is firing. Thus, as much as **1.2** g may be produced by the retrorockets during the short period that all three retrorockets are firing simultaneously, The Astronaut must also perform the reentry rate-damping task under acceleration levels as high as **8** g during a normal flight and higher in an abort.

In the most recent Mercury training program, a simulated Mercury instrument panel and hand controller were mounted in the Johnsville centrifuge gondola. In addition, the gondola could be depressurized to the 5-psi level of the Mercury capsule in orbit. At this ambient pressure level, it was possible to operate with either a soft or pressurized suit. Performance data were collected both with the centrifuge turning under dynamic (**2.2** *g* during retrofire or **11** g during reentry) and under static (**1 g**) conditions to determine the effect of varying acceleration levels on the Astronaut's ability to control the vehicle. For training purposes, the control tasks were made more difficult than the expected flight conditions,

The trends established indicate a decrease in performance due to acceleration and pressure-suit inflation. Preliminary analysis of the performance data obtained during the retrofire task shows that, under acceleration, error increased in both suit conditions and is particularly marked in the hard-suit condition. No significant change in performance was noted during static runs between soft- and hard-suit conditions. In re-entry rate damping tasks, once again error increased under dynamic conditions and the effect of suit pressurization was greater under acceleration. These results tend to confirm the general pattern observed for the retrofire conditions. An important consideration in planning the Mercury training program was the amount of centrifuge training required. These data seem to demonstrate the desirability of training in a simulated acceleration environment and for making provision for the use of the pressure suit during such training.

Experience to date indicates that the control systems are adequate to the problems presented to the Astronaut and that he is developing through the training program a high level of skill in performing control tasks. It is hoped that this brief review will point out the extent to which the Astronaut operates as an integral part of the Mercury system and the opportunity the Mercury flight provides for demonstrating man's proficiency as a controller for space vehicles. ♦♦

## Astrobee 1500 Up for Launch



Last December, this Astrobee **1500** released three sets **of** flares at an altitude **of 1361** mi., midway between California and the Hawaiian Islands, in an AFCRL experiment to position the Islands geodetically. The two-stage vehicle, developed **by** Space-General Corp., consists **of** tandem Astrobee **250** (first stage) and **Alcor** solid rockets. **It** can carry a **50-lb** payload **to** an altitude **of 2000** mi. or **200** lb to an altitude **of 1100** mi.