

DYNAMIC SIMULATORS FOR TEST OF SPACE VEHICLE

ATTITUDE CONTROL SYSTEMS

by

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INTRODUCTION

Both manned and unmanned spacecraft are designed to carry out a variety of missions in support of NASA programs for the exploration and exploitation of space. The great majority of these spacecraft require some sort of attitude control in order to carry out their assigned mission. The scientific spacecraft utilize radio to transmit their data back to earth so it is necessary to point an antenna. Many satellites depend upon panels of solar cells to supply power and hence the satellite must be oriented so that the panels receive maximum solar radiation. The nature of certain scientific experiments requires that instruments maintain a specified orientation, in the case of one of the largest and most complex satellites, the orbiting astronomical observatory (OAO), the entire spacecraft must be precisely pointed at a star in order to observe it with the large telescope rigidly

mounted to the vehicle. Spacecraft designed for lunar or planetary missions will be required to make trajectory corrections in route so the thrust vector must be properly oriented. A precise thrust vector orientation must also be achieved in order to go into orbit around the moon, or a planet, or to re-enter the earth's atmosphere from orbit.

There are four primary factors that determine the performance of a spacecraft attitude control system. They are:

- (a) Spacecraft inertia
- (b) External torques (solar pressure, gravity gradient, micrometeorites)
- (c) Applied torque (from controller)
- (d) Attitude sensors

In the development of a control system these factors must be considered during the analytical formulation, and they are likewise important for dynamic system simulation which has come to play an essential role in the verification and refinement of performance when actual components are employed.

Two important and unique features of the space environment especially pertinent to attitude control systems are the cancellation of gravity effects by the trajectory acceleration, and the virtual absence of frictional resisting torques due to the near vacuum environment. These features can be accounted for during analytic investigation and computer simulations, but present a problem for simulation studies that involve physical equipment. No method of simulating zero gravity is available in the laboratory although gravity effects can be minimized in a dynamic simulation to the extent that the center of rotation can be made to coincide with the center of gravity. The most satisfactory way to simulate the low friction aspect of the space environment is by the use of the airbearing supported test platform, and the remainder of this paper will deal with the design and use of airbearing platforms for space vehicle attitude control system studies and tests. It

will be shown that the airbearing platform provides a mounting of extremely low friction with wide orientation capability. It does not duplicate the zero gravity effect, but it can permit sensitive balance to bring the center of gravity very close to the center of rotation and hence minimize pendulous effects. Essentially, the airbearing platform permits an accurate representation of spacecraft inertia and realistic use of the actual vehicle attitude control torque sources and sensors.

#### THE AIRBEARING PLATFORM

Figure 1 is a picture of an airbearing supported platform constructed at NASA Ames Research Center in 1959. It may appear very simple compared to the present state of the art as exemplified by several large and complex facilities in the aerospace industry, but it illustrates most of the fundamental advantages and problems of airbearing tables. The table is supported by a 5-inch-diameter spherical aluminum bearing which has a cylindrical neck to which the frame of the platform is bolted. The bearing seat is a matching hemisphere of epoxy resin cast into a metal cup that rests upon a four-legged support to the floor. The raised center construction puts the center of rotation about three inches above the working platform to minimize the need for extra balance weights to maintain the platform in pendulous balance as attitude control equipment is added to the platform. A major effort is made to keep the table center of rotation and center of gravity coincident so that gravity effects will be avoided. In fact, a fundamental and ubiquitous problem in the use of airbearing platforms is to avoid torques due to gravity unbalance. The use of stiffened rib construction in this platform is an attempt to prevent platform flexure with changes in pitch and roll. Such flexure is termed an

anisoelastic effect and considerable theoretical and design effort is expended to minimize the resultant gravity torque in the most precise facilities. The platform in Figure 1 supports an optical sensor to provide an electrical error signal as the platform attempts to drift from a desired orientation. This error signal actuates the inertia wheels which develop a torque to maintain the desired platform attitude. It will be noted that these wheels are in a plastic enclosure to assure that they provide torque only by their inertial effect and not by friction against the air.

Figure 2 is a photograph of a similar platform in operation with a more elaborate control system. The entire platform is enclosed beneath a hood to avoid thermal air currents in the laboratory that can cause serious interference torques, a manifold is also installed around the spherical bearing to pump off the air used for support, a number of small wires are brought from the base to the table around the airbearing. This causes a slight interference torque but permits operational flexibility by providing electrical power and instrumentation connections to the laboratory bench. Two two-axis star trackers are mounted on the table to give control signals in all three axes. Three torquers are used, each of which utilizes a pair of control moment gyros (Ref. 1). This equipment was used to investigate dynamic performance when the table was displaced through small angles from the reference light sources - about 1/2 degree. It was necessary to tape all wires to the table as slight shifts with table attitude changes caused unbalanced effects. This equipment was able to maintain its reference attitude within about one second of arc in all three axes.

#### IMPORTANT CONSIDERATIONS IN AIRBEARING TABLE DESIGN AND OPERATION

The foregoing pictures and descriptions of specific test platforms will

serve to introduce the subject of design problem areas which is the primary concern of this paper.

Design problems arise because it is desirable from a research standpoint (and the airbearing platform is essentially a research tool) to provide maximum convenience in the operation of the platform and at the same time to maintain all interfering disturbance torques at a very low level to simulate their absence in space. The most important operational flexibility requirements include the ability to substitute various pieces of equipment on the platform quickly; the ability to supply electrical power to equipment on the table; the ability to measure the instantaneous attitude of the table; the ability to utilize a variety of platform torque sources including inertia wheels, control moment gyros, magnetic field torquers and gas reaction jets; and the ability to use various tracking devices such as star trackers, planet trackers, sun trackers, horizon scanners and inertial sensors.

The most straightforward way to carry out equipment modifications on an airbearing platform by simple interchange of components would introduce significant unbalance torques. A major design effort is therefore expended in providing the required operational flexibility by means that keep the interfering torques at an acceptable level. In general, the replacement of a piece of equipment will cause a shift of the platform center of gravity away from the center of rotation and the resulting unbalance torque due to gravity will be balanced out by shifting adjustable weights on the platform.

In order to judge how serious various disturbing torques are, the following is an estimate of disturbance torques that will act upon an actual satellite in orbit. One of the largest NASA scientific satellites that will require very precise attitude control will be the Orbiting Astronomical Observatory. As shown in Figure 3, it will approximate a cylinder 6 feet in

diameter and 10 feet long. It will weigh 3600 pounds and have a maximum moment of inertia of 1450 slug feet squared. While in orbit at 500 miles, it will experience gravity gradient torque of 600 dyne cm, radiation torque of 150 dyne cm, aerodynamic drag torque of 150 dyne cm, and magnetic torque of 600 dyne cm. The control system must be designed to cope with these torques in space as well as to change satellite attitude on command. It would be desirable if the interfering torques acting on a ground based airbearing facility used to simulate the control system operation could be kept below these values. This level of disturbance torque is however quite low and very difficult to obtain in a ground based environment. It will be recalled that the dyne cm is an extremely small unit of torque; an ounce inch is 70,615 dyne cm, and a foot pound is 13,558,200 dyne cm.

#### PLATFORM DISTURBANCE TORQUES

The disturbance torques acting on an airbearing table have been categorized into the four groups of Figure 4. These torques will be considered in sequence.

The first group depends upon the construction of the airbearing platform itself. The first five platform torques in the first group are basically due to gravity acting on a shift of the center of mass from the center of rotation. They are minimized by construction of a platform that is very rigid and made from materials that do not deform as the platform attitude is changed, or as temperature changes. Solenoid valves used to release jet thrust or relays used to cage gyros will cause impulsive torques, and unbalance torques as the selenoid element shifts position.

The second group of torques arise in the support. The airbearing itself

contributes aerodynamic turbine torques if the airflow is not precisely symmetrical. Exhaust air impingement on the platform due to imperfect scavenging of the bearing also produces a torque.

The environmental torques of the third group are particularly troublesome. An aerodynamic damping torque will arise as the platform moves through the air. Some large industrial facilities have placed the entire table in a vacuum chamber to eliminate this torque. One of the most serious torques is due to the effect of stray air currents acting on the platform. It may not be convenient to place the platform in a vacuum chamber, but work to any reasonable degree of precision requires that the platform be located within some sort of shielding enclosure. An effort should be made to construct the table from nonmagnetic materials. Some current research platforms are placed between three pairs of large Helmholtz coils which can neutralize the earth's field. Vibration effects are minimized by mounting the airbearing support pedestal on an isolated seismic block.

The fourth group of torques in Figure 4 depends upon the particular scheme used to mechanize the control system being tested. Unbalance torques due to unsymmetrical depletion of tanks as compressed gas is used for reaction thrust can be appreciable. Even carefully balanced pairs of compressed gas tanks with a common manifold are still troublesome as they expand under pressure and shift slightly. Mass unbalance torques within batteries as they discharge are so difficult to compensate that research investigations frequently utilize laboratory electrical power supplies with very flexible leads dropped into the center of the platform. For research purposes the requirements for frequent modification of equipment are so important that some sort of automatic or semi-automatic balance system is needed. A simple arrangement of three weights that can be motor driven linearly along mutually perpendicular directions can be

controlled by an operator observing table motion or can be slaved to sensitive rate gyros or linear accelerometers to achieve rebalance after any change of platform load.

#### PLATFORM BALANCE CALCULATIONS

Figure 5 illustrates an unbalance with the platform horizontal because the center of gravity is displaced horizontally and vertically by distances  $x$  and  $y$  from the center of rotation. When the platform rotates through an angle  $\theta$  from its horizontal position the torque due to gravity is

$$T = -Mgx \cos \theta - Mgy \sin \theta \quad (1)$$

If the platform is allowed to oscillate as a pendulum through a very small angle, the period will be

$$T = 2\pi \sqrt{\frac{I}{MgL}} \quad (2)$$

(for very small unbalance, the moment of inertia  $I$  measured about the center of rotation is very close to  $I$  measured about the center of gravity). The period can be used to compute the distance  $L$  between the center of rotation and center of gravity. Practical measurements of unbalance involve instrumentation techniques that will be discussed later, but if it is assumed that platform angles and external applied forces can be measured to great enough precision, then certain simple calculations can help greatly in the actual task of balancing a platform.

The horizontal shift of the center of gravity can be determined by measuring the externally applied torques  $T_1$  and  $T_2$  required to maintain the platform at equal and opposite angles  $\theta$  and  $-\theta$ . Applying equation (1) with applied torque equal to minus gravity unbalance torque

$$T_1 = Mgx \cos \theta + Mgy \sin \theta \quad (3)$$

$$T_2 = Mgx \cos \theta - Mgy \sin \theta \quad (4)$$

$$x = \frac{T_1 + T_2}{2Mg \cos \theta} \quad (5)$$

$$y = \frac{T_1 - T_2}{2Mg \sin \theta} \quad (6)$$

For example, in simulating a spacecraft as large as the Orbiting Astronomical Observatory with a weight of 1600 kilograms and a 2000 kilogram meter squared moment of inertia, a horizontal center of gravity displacement of one hundredth of a cm would produce a gravity unbalance torque of

$$T = -Mgx = 1600 \times 10^3 \times 980 \times 10^{-2} = 15.7 \times 10^6 \text{ dyne cm}$$

For another example, a center of rotation - center of gravity shift of a hundredth centimeter would produce a pendulous period of

$$T = 2\pi \sqrt{\frac{I}{MgL}} = 2\pi \sqrt{\frac{2000}{1600 \times 9.8 \times 10^{-4}}} = 224 \text{ sec}$$

Anisoelastic effects are due to deformations of the platform that change

as the platform angle with respect to gravity changes. Figure 6 shows these effects. The top left figure shows an undeformed platform as it would appear in the absence of gravity. The top right figure shows a deflection due to the effect of gravity acting on the mass of the table which is assumed to be concentrated in two blocks which each exert a torque  $MgL/2$  to bend the table. Each block is deflected downward a distance  $d_0$ . It is assumed that the platform center of gravity and center of rotation coincide in this normal gravity loaded position. The bottom figure shows how the platform begins to straighten out as it tips. The torques causing platform deflection are reduced from  $MgL/2$  to  $(MgL/2) \cos \theta$ .

Since the deflection is small and varies from a maximum ( $d_0$ ) for the platform level at  $\theta = 0$  to zero when the platform is vertical  $\theta = 90^\circ$  it is a reasonable approximation to assume that the deflection varies proportionally to the torque and at any tilt angle  $\theta$  would be  $d = d_0 \cos \theta$ . The distance by which the center of gravity rises above the center of rotation perpendicular to the platform as the platform tilts, is

$$e = d_0 - d = d_0(1 - \cos \theta)$$

At any tilt angle  $\theta$  this center of gravity shift causes a disturbance torque

$$Mge \sin \theta = Mgd_0(1 - \cos \theta) \sin \theta = Mgd_0(\sin \theta - 1/2 \sin 2\theta)$$

It is interesting to note that the disturbance torque due to anisoelasticity has components proportional to both  $\theta$  and  $2\theta$ . A numerical example for the platform values considered previously with a maximum bending deflection of  $d_0 = 0.01$  cm shows an unbalance torque at  $20^\circ$  of

$$T = 1600 \times 10^3 \times 980 \times 10^{-2} \left( 0.34202 - \frac{0.64279}{2} \right)$$

$$= 318,000 \text{ dyne cm}$$

Another interesting disturbance torque that can act upon a platform is due to gravity gradient. The force of gravity falls off inversely as the square of the distance from the center of the earth. A simplified analysis would consider that at a reference level it would be  $g_0 = G/R^2$  where  $R$  is the radius of the earth at the reference. At an altitude  $h$  above the reference level it would be  $g = G/(R + h)^2$ . In Figure 7 the table is tipped through an angle  $\theta$  so the vertical displacement between the two concentrated centers of mass is  $h = 2L \sin \theta$ . If the torque due to the lower mass at the reference altitude is  $(M/2)g_0 L \cos \theta$ , that due to the upper mass is  $-(M/2)gL \cos \theta$  so the net torque is

$$T = \frac{ML}{2} \cos \theta [g_0 - g]$$

$$= \frac{ML}{2} \cos \theta \left[ \frac{G}{R^2} - \frac{G}{R^2 \left( 1 + \frac{h}{R} \right)^2} \right] \approx \frac{ML}{2} \cos \theta \left[ \frac{G}{R^2} \frac{2h}{R} \right]$$

if terms in  $h^2$  are dropped. Inserting the expressions for  $h$  and  $g$  the next torque due to gravity gradient is then

$$T = 2M \frac{g_0 L^2}{g_0} \frac{\cos \theta \sin \theta}{R} = \frac{M g_0 L^2 \sin 2\theta}{R}$$

It is interesting to note that this is a function of twice the tilt angle in a fashion similar to anisoelastic torque. For the previous example with two

800 kilogram concentrated weights one meter apart at a tilt angle of 30° and  
R = 6371 km

$$T = \frac{1600 \times 10^3 \times 980 \times 50^2 \times 0.866}{6371 \times 10^5} = 5340 \text{ dyne cm}$$

This simplified analysis neglects the fact that the radii from the center of the earth to the two concentrated masses are not strictly parallel. A more rigorous derivation (Ref. 2) would reveal that the gravity unbalance torque is increased 50% by this effect from

$$\frac{M g_o L^2 \sin 2\theta}{R} \text{ to } \frac{3}{2} \frac{M g_o L^2 \sin 2\theta}{R}$$

#### OPERATIONAL AIRBEARING PLATFORMS

The next few figures will illustrate some currently operational platforms that have been used to investigate a variety of satellite attitude control systems. They will give an idea of the designs used by different groups and indicate some of the possible refinements that have been employed.

##### a. Jet Propulsion Laboratory

Figure 8 is a photograph of a platform developed by the Jet Propulsion Laboratory. This platform represents the second generation of airbearing equipment developed at JPL and incorporates several interesting features. The platform is made very stiff by the use of heavy metal plates in a webbed construction so unbalance torques due to platform deformation are kept below 10 gram cm. Stainless steel construction is used to minimize magnetic torques from the earth's field. The platform weighs 800 pounds before mounting any

experimental equipment. A 30-channel telemetry system is utilized instead of any wires between the platform and the laboratory. Sealed nickel cadmium batteries are used for power on the platform. They contribute less than 5 gram cm torque for a 90° platform tip. An automatic balance system drives weights along three axes in response to sensitive rate gyro signals to achieve static balance before testing. The bearing is a 10-inch-diameter beryllium ball spherical to within  $\pm 30$  micro inches. The bearing pad is 5 inches across and has two concentric circles of air jets, one circle 1-1/2 inches in diameter has ten jets. The other circle 3.6 inches in diameter has 23 jets. The pad mounting assembly provides a nylon ring as a support for the ball and table at times when there is no air pressure applied. The bearing pad itself is so constructed that it rises as a piston with air pressure. About 140 psi air supply is required to float the table. An attitude control system mounted on the table has included gyros, sun sensors, canopus sensor and control jets. Figure 9 shows the offset pedestal which allows the platform to tip past 90°. Figure 10 shows how the entire pedestal can be motor-driven to swing out of the way to allow maximum tip in any direction.

b. Ames Research Center

Figure 11 is a sketch of an airbearing supported man-carrying platform used at Ames Research Center of NASA to evaluate twin gyros as an attitude control torque source (Ref. 1). Star trackers with a resolution of 2 arc seconds were used as attitude sensors. The passenger was constrained to a movement while manipulating a theodolite as a planet tracker. The control system was able to maintain the platform attitude to within 5 arc seconds. Figure 12 is a photograph of this platform. Compressed air was used to unload the twin gyro controllers; motor-driven balance weights along three axes were used for static balance. The platform weighed 1800 kilograms and was

supported on a 24-cm stainless steel ball in an epoxy resin seat by about 300 psi air through a single hole in the bottom of the bearing seat.

c. Langley Research Center

Figure 13 is a photograph of an airbearing supported platform used at the Langley Research Center of NASA to investigate a wobble damper for a spinning satellite (Ref. 3). The platform is supported by a 6-inch-diameter stainless steel ball in an epoxy resin seat. Air at 20 psi is admitted through a 0.09-inch-diameter hole in the bottom of the seat. After this platform is spun up to about 20 rpm by the motor mounted on the overhanging beam, the beam is swung out of the way to allow the platform  $\pm 20$  degrees of freedom to tip about a horizontal axis.

Figure 14 is a photograph of another airbearing platform that was used at the Langley Research Center to test a satellite attitude control system using both inertia wheels and a large bar magnet (Ref. 4). This table was supported by a 3-inch-diameter brass ball in an aluminum seat. Air at 15 psi was admitted through 12 holes located around the cup. Power was connected to the platform through small-coiled wires suspended above the center of the table.

d. Marshall Space Flight Center

Figure 15 is a photograph of an early airbearing table constructed by the Marshall Space Flight Center of NASA. The offset support permits  $\pm 120^\circ$  attitude change in roll and pitch and unlimited freedom in yaw (Ref. 5). The bearing is a 10-inch-diameter ball manufactured to a tolerance of 50 millionths of an inch. Air is admitted to the bearing cup through tiny holes arranged in two concentric circles and is vented both at the edge and at the center of the cup. The platform is balanced by first applying a brake to the ball to keep the table stationary, and then measuring table motion when the brake is released. Balance weights are then adjusted to minimize the motion. Two rather clever

devices are employed for fine balance. Steel strips are attached to the platform by nylon mounting pads whose large temperature coefficient causes a shift in the center of gravity of the steel strips to compensate for temperature effects on the table as a whole; also three pairs of cantilever springs with weights attached can be used to compensate for anisoelastic torques by generating a torque which to a first approximation varies with the sine of twice the deflection angle of the platform. No external connections are made to this table, dry cell batteries are used on the platform, and information from the control system is telemetered out.

Figure 16 illustrates a second generation platform recently installed at Marshall Space Flight Center. This platform is a highly symmetrical disc-shaped body and offers extreme rigidity and large moments of inertia with minimum mass. The platform is built of nonmagnetic material (aluminum) and is specially treated to prevent warping. The bearing consists of an aluminum sphere and cup. To balance the simulator it is temporarily constrained to rotate about a single axis by means of a small auxiliary spherical airbearing which can be attached to the platform at any of three locations which represent three orthogonal axes about which balance is to be achieved. Acceleration is then measured about the axis of freedom in order to compute the unbalance torque. A recent communication from Marshall made the following comments about this platform:

At Marshall the major problem encountered while attempting to employ the simulator for control system studies has been that of achieving and maintaining balance at any angular position. The sources of unbalance that exist in general and current methods of overcoming them are tabulated below:

1. Torque caused by platform deformation which results from:
  - a. Heating by radiation from external reference sources such as sun, star or earth simulators.

- b. Heating by radiation and conduction from onboard instrumentation.  
(No completely satisfactory solution for a and b.)
  - c. Changes in the ambient temperature of the room.  
(Solved by very accurate control of room temperature.)
  - d. Gravity anisoelasticity torques. (Solved by cantilever spring mass compensators.)
2. Airbearing or "turbine" torques.
  3. Torques due to nonsphericity of the bearing. (Both 2 and 3 solved by holding airbearing manufacturing tolerances to the minimum allowed by the state of the art - ten millionths of an inch.)
  4. Torques caused by air currents which result from:
    - a. Room air conditioning system.
    - b. Convection currents from hot equipment in the room or onboard the simulator. (A complete solution would require operation in a vacuum chamber. A close fitting enclosure and shutdown of room air conditioning and ventilation will help.)
  5. Torques caused by shift of the center of mass of onboard batteries.  
(No satisfactory solution. It has been determined that the mass shift is a function of angular position, time in the angular position, and discharge rate.)
  6. Torques caused by shift of mass of onboard instrumentation.
    - a. Relay armatures. (Solved by use of solid state switching or employment of balanced armature relays.)
    - b. Deformation of wiring harnesses and components. (Solved by constructing rigid containers with securely attached components and solidly anchored to the platform. All wiring harnesses are potted and anchored.)

7. Torques caused by shift of the composite mass of the simulator due to depletion of an onboard propellant supply - compressed gas.  
(Solved by making the center of mass of the propellant cavities coincident with the center of rotation of the platform.)
8. Torques caused by gravity gradient. (Solved by use of the aniso-elasticity compensators since it is a function of twice the tilt angle of the platform.)
9. Torques caused by the earth's magnetic field. (Solved by using 3 pairs of Helmholtz coils to cancel the earth's field.)

e. United Aircraft Corporation

There are several large and complex airbearing installations in industry. Three of these, those at United Aircraft, Grumman, and General Electric, will be described to fill out the picture of existing research facilities.

Figure 17 is a picture of the airbearing facility at United Aircraft Corporate Systems Center, Farmington, Connecticut. This platform is distinguished by a very accurate attitude measurement system. The 5-foot-diameter table is surrounded by a three-axis following gimbal system which utilizes autocollimator signals to track the airbearing platform without any physical contact. Angular pickoffs on the gimbal axes then provide attitude data for the platform to within a few seconds of arc. The platform is supported on a 16-inch-diameter airbearing. The sphericity of the ball is within approximately 100 micro inches; it has a surface finish of 5 micro inches. The bearing is supported with dry nitrogen at 250 psi and about 12 cubic feet per minute. With a full load of 8000 pounds on the platform the clearance between the bearing and its seat is about 0.001 inch. There are no external wires connected to the table. All instrumentation power is supplied from onboard batteries and data is telemetered from the table. Ventilation air flow through the laboratory is

is kept to a minimum, controlled to within  $\pm 3^{\circ}$  F in temperature and filtered of dust particles larger than 0.3 micron diameter.

f. Grumman Aircraft Engineering Corporation

Figure 18 is a pictorial representation of the airbearing facility at Grumman Aircraft Engineering Corporation, Bethpage, New York (Ref.6). The platform is enclosed in a chamber that can be evacuated to 0.75 millimeters of mercury to effectively eliminate air current effects which are a very troublesome source of extraneous torques. Three pairs of Helmholtz coils 14 feet in diameter surround the platform to first neutralize the earth's magnetic field and then simulate on a dynamically programmed basis the magnitude and direction of the changing field at satellite altitude during a simulated orbit. For star tracking studies five collimators, 5 inches in diameter, are located within the chamber. They can represent stars from -1.0 to +6.0 magnitude. Each provides a star whose angular subtense is less than eight arc seconds with a parallax error less than five arc seconds. The entire chamber is mounted on a 110-ton concrete seismic foundation.

g. General Electric Company

Figure 19 is a photograph of one of the airbearing installations at the General Electric Company, Space Technology Center, Valley Forge, Pennsylvania (Ref.7). The photograph shows an engineering mock up of the orbiting astronomical observatory mounted on a 10-inch-diameter stainless steel ball. The photograph was taken during the fine balance of the platform and small catenary chains connected from the platform to supporting posts can be seen. This is part of their "chain-o-matic" procedure for balance. This procedure utilizes the chains to apply a proportional restoring torque to the platform so that the oscillation period is shortened by an order of magnitude. This allows much more rapid adjustment of weights for fine balance. Balance shifts due to

temperature changes have been overcome by maintaining full electrical power to the test platform on a continuous 24-hour-a-day basis.

Another development platform at General Electric has interesting features. Attitude is read out to a few seconds of arc by a small three-axis following gimbal system built around the bearing support beneath the platform. Mounted on this gimbal system are magnetic torques that can apply precisely measured torques to the platform at any attitude. In conjunction with the precision attitude measuring system this permits the kind of torque and angle measurements discussed in the section on platform balance calculations. An additional feature of this platform is the use of a ball support with a 1/2-inch-diameter hole drilled clear through so that air from the bearing support can be transferred to the platform for use in air jet attitude control systems without the unbalance that can occur as onboard tanks are depleted.

#### CONCLUSIONS

It seems apparent that the technology of airbearing platforms has moved swiftly from a simple qualitative research tool some five or six years ago, to a complex and potentially quite precise quantitative instrument for investigation of a wide variety of attitude control research problems and performance verification studies. In order to overcome the numerically small but theoretically important extraneous platform torques due to gravity unbalance, and externally applied forces, it appears necessary to construct rather elaborate facilities. The possibility of quite precise quantitative numerical data is presented by such features as: isolation in a vacuum chamber and construction of a following gimbal system for attitude readout with its additional use for applying calibration torques to the platform and providing a virtually disturbance free means for connecting electrical wires to the platform.

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**EARLY AIR BEARING PLATFORM  
AMES RESEARCH CENTER - 1959**

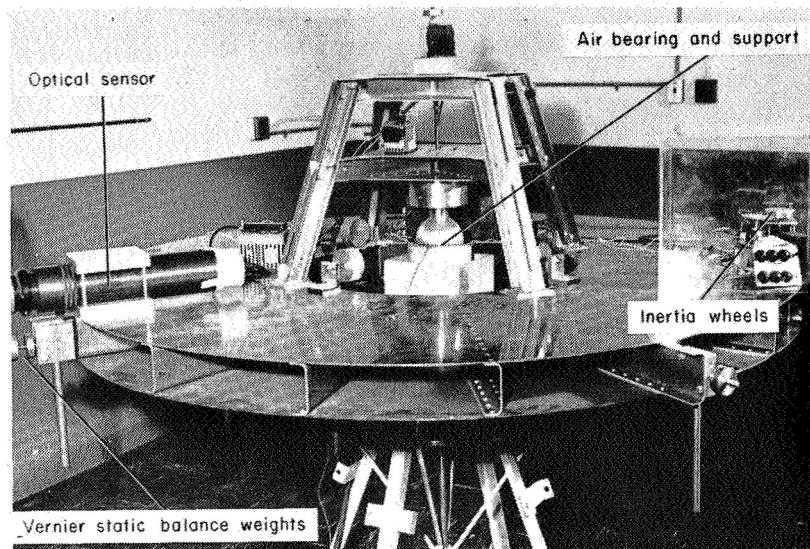


Figure 1

**PLATFORM WITH TWIN GYRO ATTITUDE CONTROL SYSTEM**

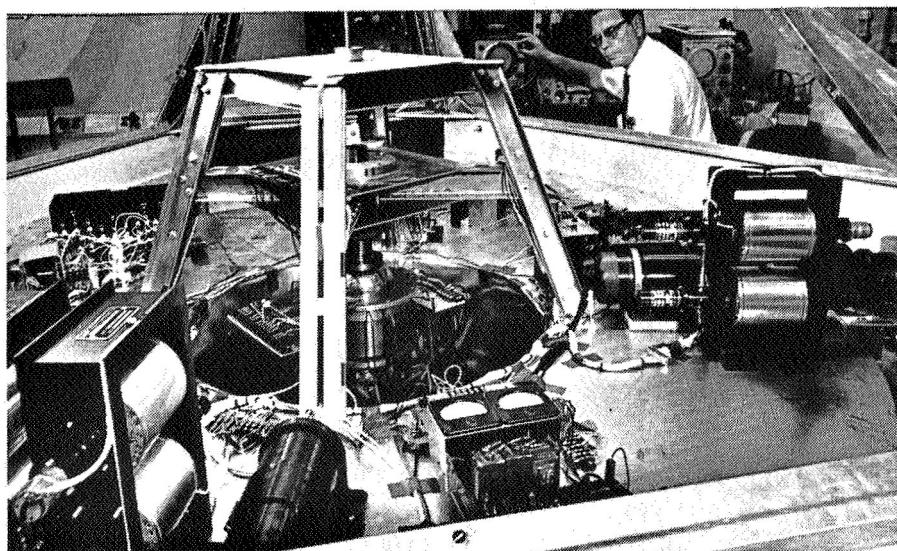


Figure 2

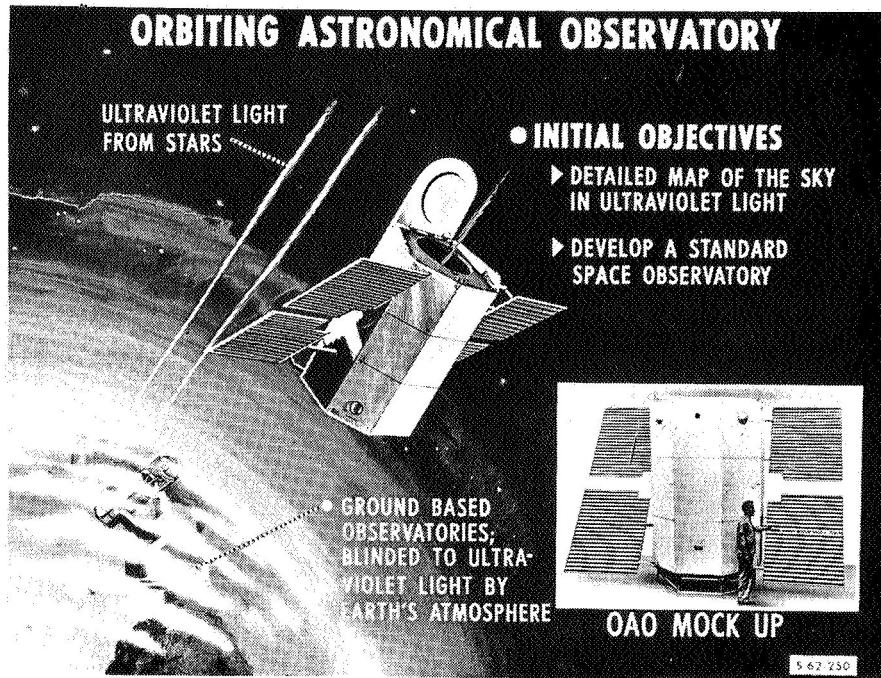


Figure 3

### DISTURBING TORQUES ON AN AIR-BEARING PLATFORM

- |  |   |
|--|---|
| <b>I TORQUES ARISING FROM PLATFORM</b> <ul style="list-style-type: none"> <li>STATIC UNBALANCE</li> <li>DYNAMIC UNBALANCE</li> <li>ANISOELASTICITY</li> <li>MATERIAL INSTABILITY</li> <li>STRESS-TEMPERATURE-HUMIDITY-EVAPORATION</li> <li>GRAVITY GRADIENT</li> <li>EQUIPMENT MOTION</li> <li>SOLENOIDS-RELAYS</li> </ul> | <b>III TORQUES FROM ENVIRONMENT</b> <ul style="list-style-type: none"> <li>AIR DAMPING</li> <li>AIR CURRENTS</li> <li>MAGNETIC FIELDS</li> <li>VIBRATION</li> <li>RADIATION PRESSURE</li> </ul>   |
| <b>II TORQUES FROM BEARING</b> <ul style="list-style-type: none"> <li>AERODYNAMIC TURBINE EFFECT</li> <li>EXHAUST AIR IMPINGEMENT</li> </ul>   | <b>IV TORQUES FROM TEST SYSTEM</b> <ul style="list-style-type: none"> <li>ELECTRICAL WIRES TO BASE</li> <li>MASS SHIFT IN BEARINGS AND LOOSE FITS</li> <li>BATTERY DISCHARGE</li> <li>REACTION JET SUPPLY DISCHARGE</li> <li>REPLACEMENT OF COMPONENTS</li> </ul> |

Figure 4

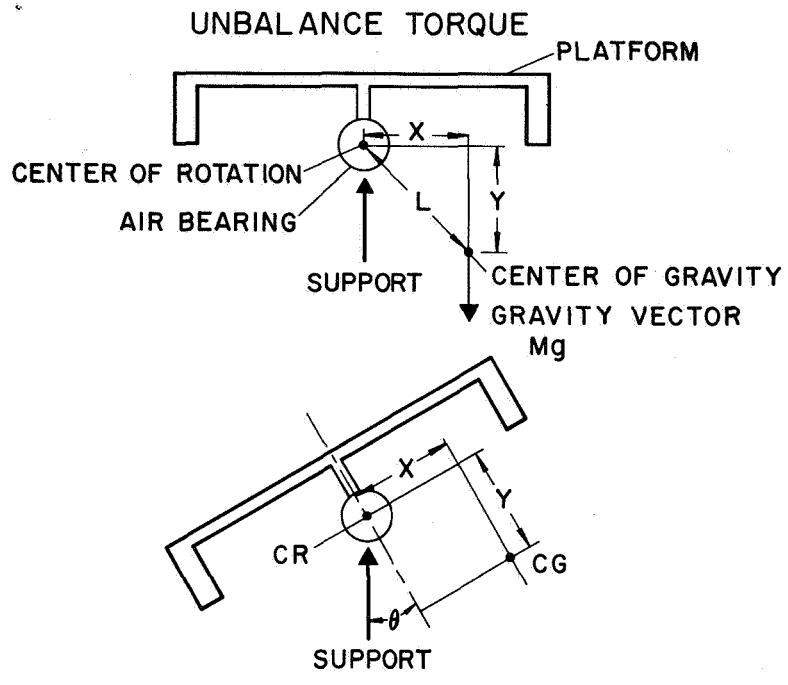


Figure 5

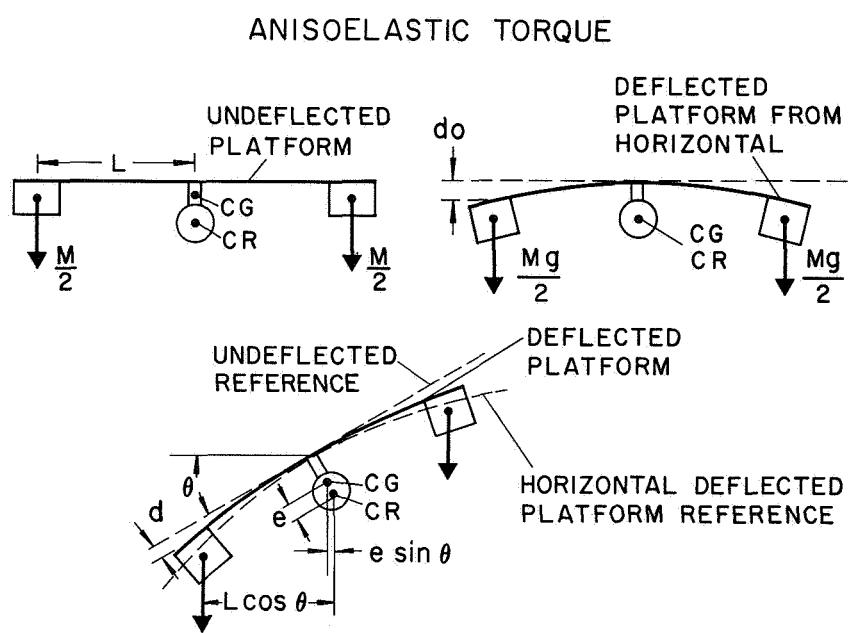


Figure 6

### GRAVITY GRADIENT TORQUE

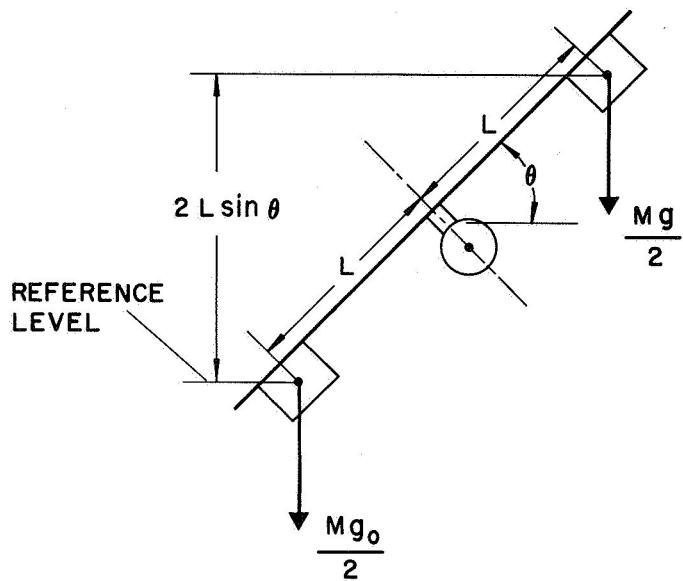


Figure 7

JPL  
AIR BEARING  
PLATFORM

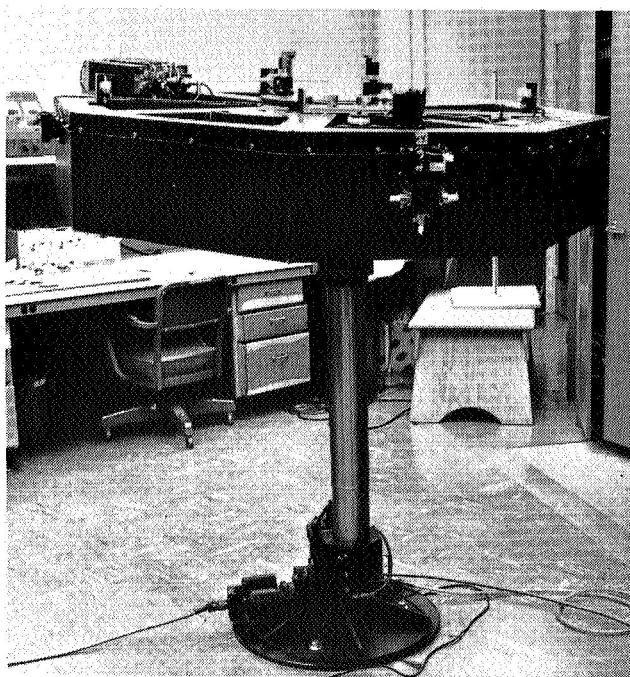
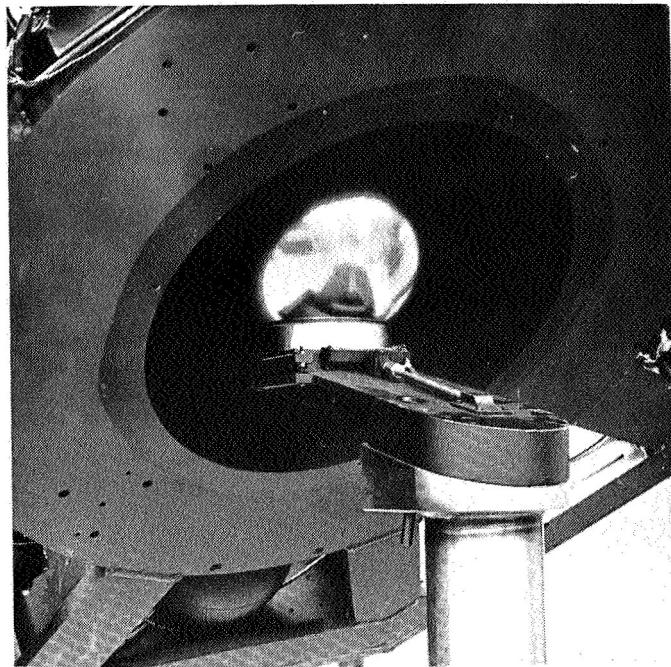
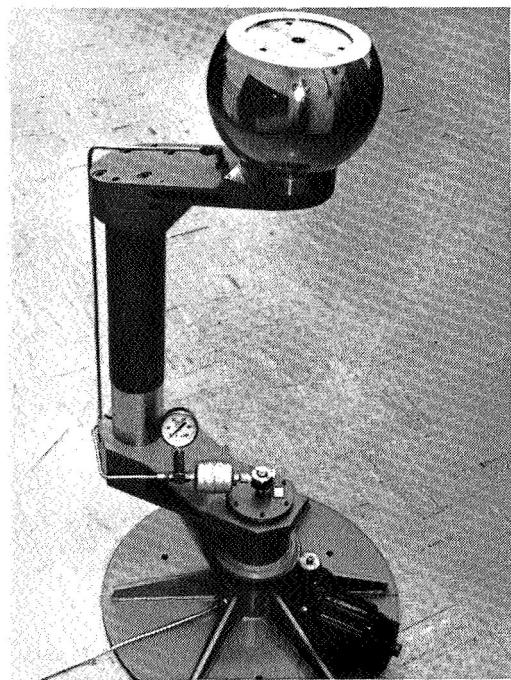


Figure 8



JPL  
ECCENTRIC  
BEARING

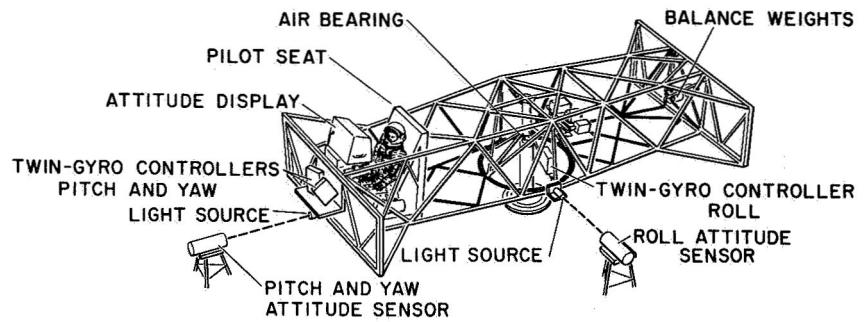
Figure 9



JPL  
PEDESTAL

Figure 10

SCHEMATIC VIEW OF SPACE VEHICLE ATTITUDE SIMULATOR



LENGTH	730 cm	ROLL MOMENT OF INERTIA	$8 \times 10^9$ gm-cm <sup>2</sup>
WIDTH	365 cm	PITCH MOMENT OF INERTIA	$9 \times 10^{10}$ gm-cm <sup>2</sup>
HEIGHT	125 cm	YAW MOMENT OF INERTIA	$1 \times 10^{11}$ gm-cm <sup>2</sup>
WEIGHT	1800 kg		

Figure 11

SPACE VEHICLE ATTITUDE SIMULATOR

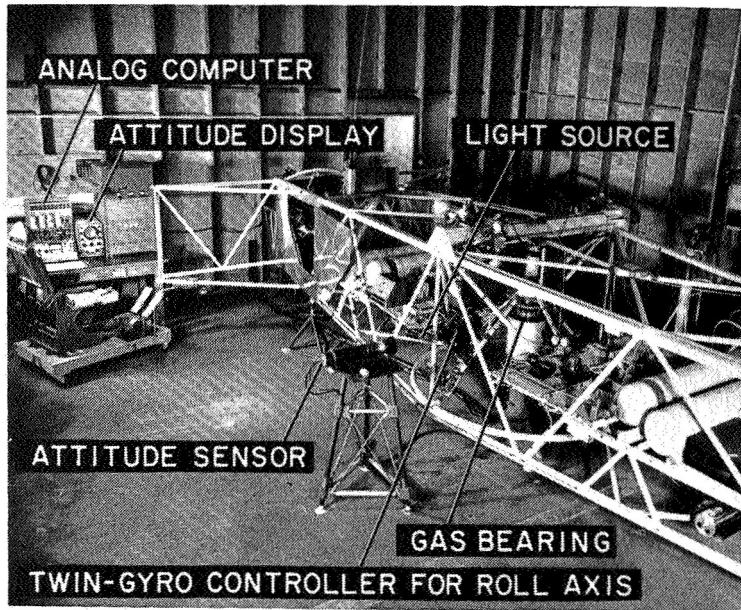
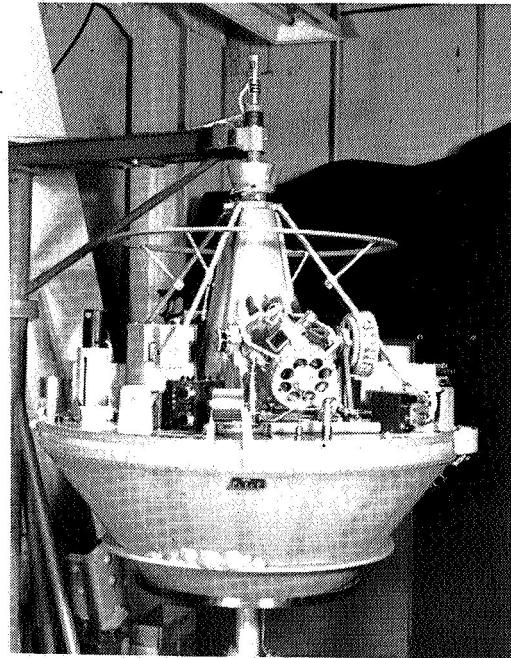


Figure 12



**LANGLEY  
RESEARCH CENTER**  
**SPINNING SATELLITE  
SIMULATOR**

Figure 13

**LANGLEY PLATFORM WITH MAGNETIC TORQUER**

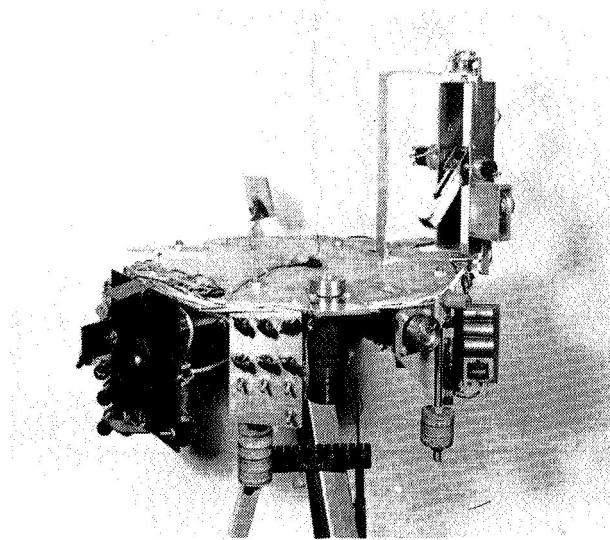
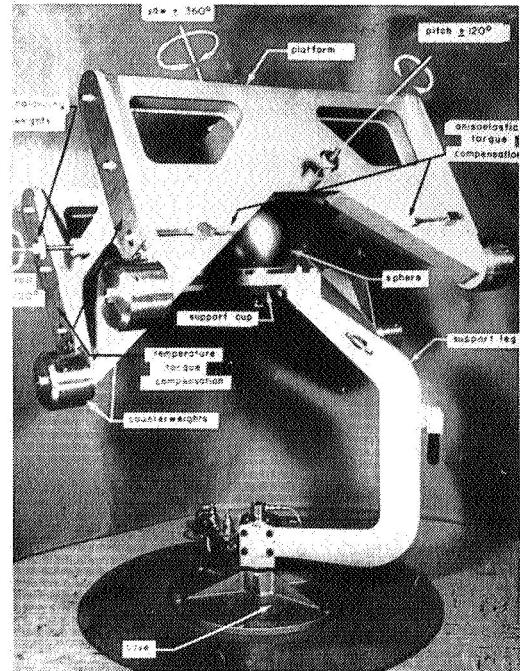


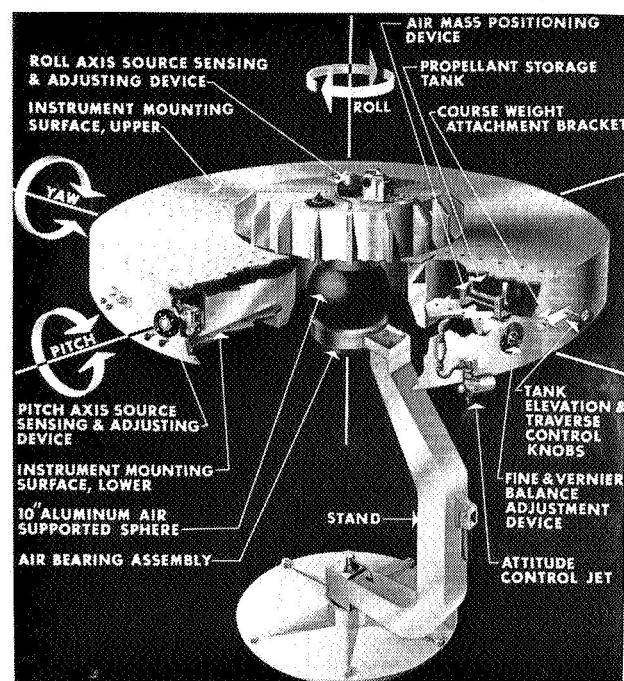
Figure 14



MARSHALL  
SPACE FLIGHT CENTER  
PLATFORM

ABOUT 1960

Figure 15



MARSHALL SPACE  
FLIGHT CENTER  
PLATFORM

SECOND GENERATION

Figure 16

AIR-BEARING TEST FACILITY WITH FOLLOWING GIMBAL  
UNITED AIRCRAFT CORP.

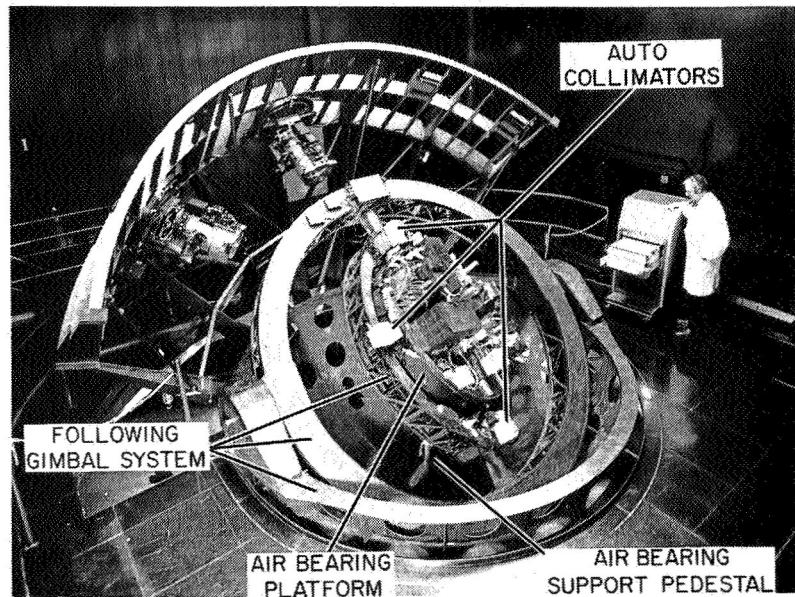


Figure 17

AIR-BEARING TEST FACILITY WITH VACUUM CHAMBER  
GRUMMAN AIRCRAFT ENGINEERING CORP.

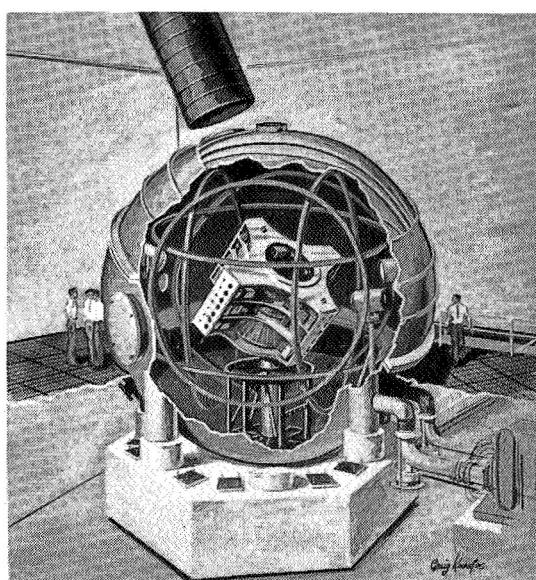


Figure 18

# AIR-BEARING TEST FACILITY

## GENERAL ELECTRIC CO.

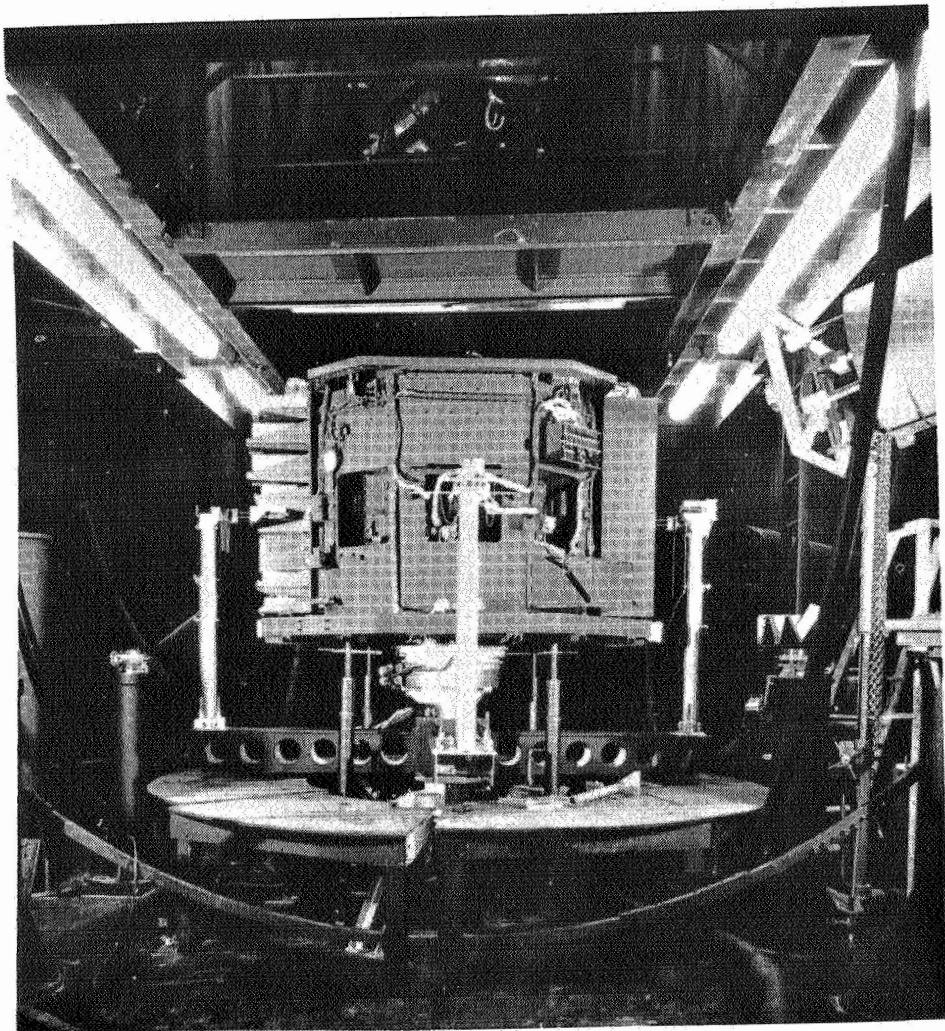


Figure 19