

SOME DYNAMICS AND CONTROL CHALLENGES THAT OCCURED DURING THE APOLLO PROJECT

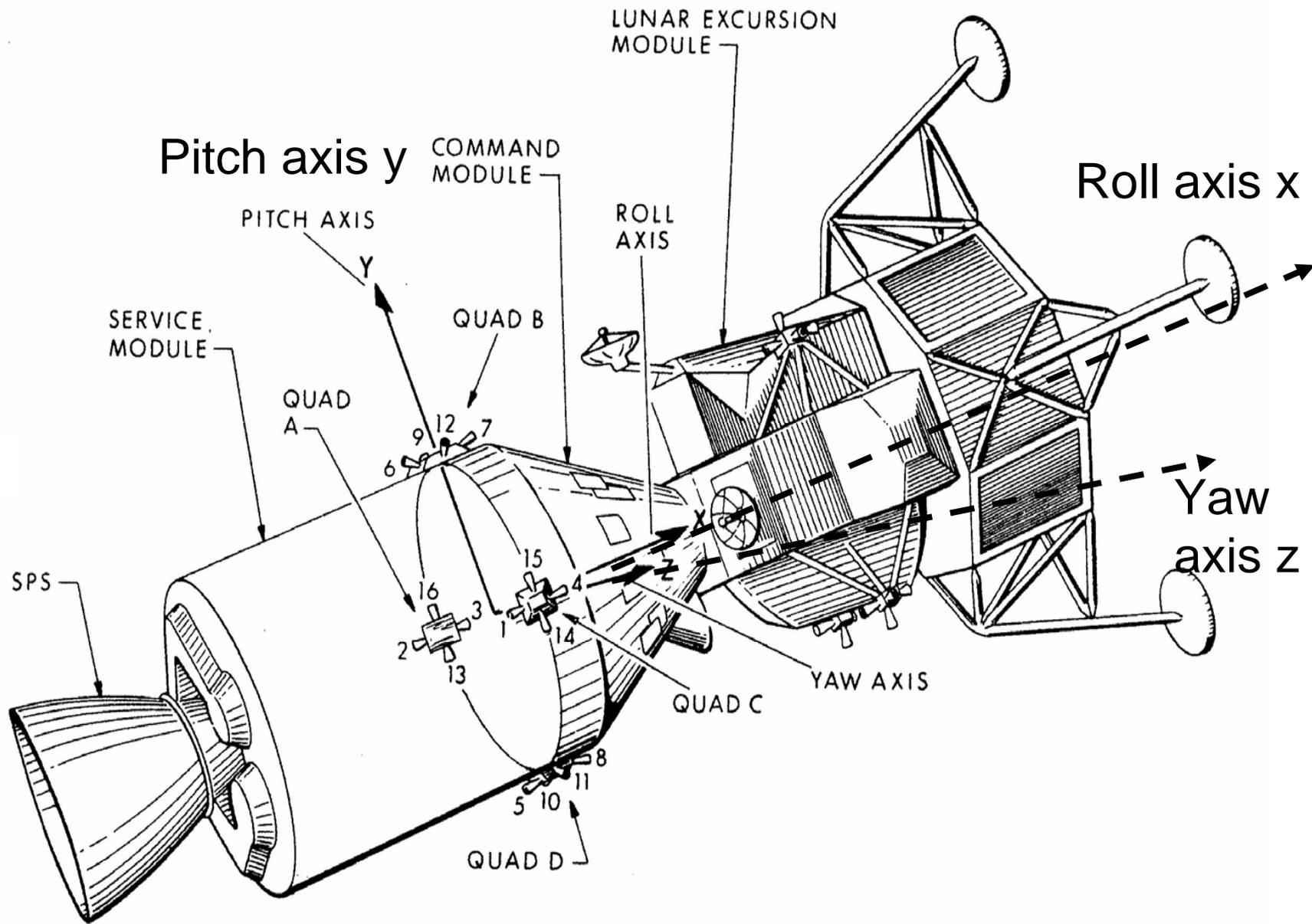
William S. Widnall, ScD

**Formerly Director, Control and Flight Dynamics,
M.I.T. Instrumentation Laboratory**

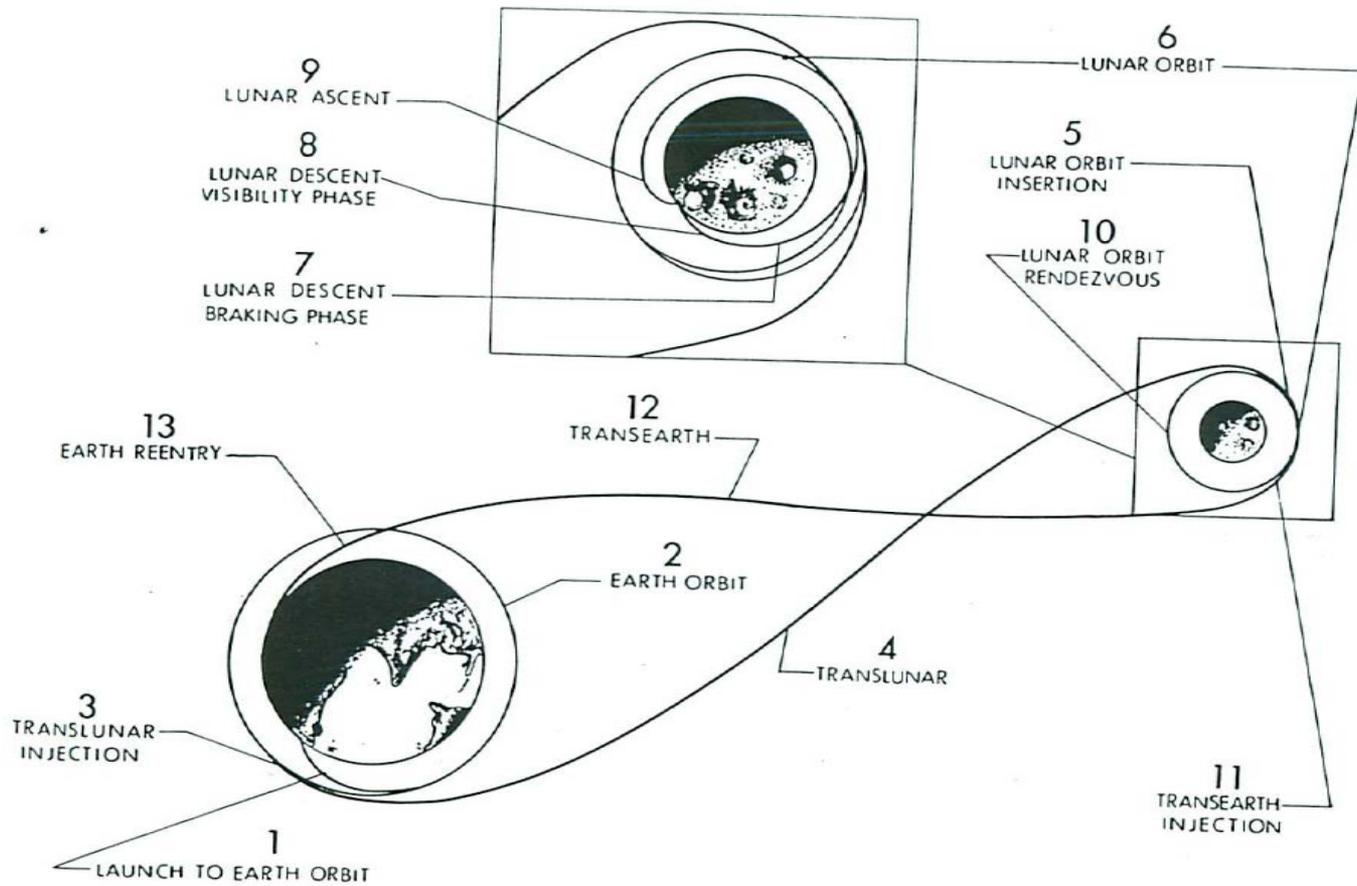
INTRODUCTION

**President Kennedy set the goal to put a man on the moon
and return him safely before the end of the 60's decade.**

**The M.I.T. Instrumentation Lab (now called the Draper Lab,
in honor of its founder) was awarded by NASA the first
prime contract -- a contract to develop the navigation,
guidance, and control system for both the Command
Module and the Lunar Module of the Apollo Spacecraft.**

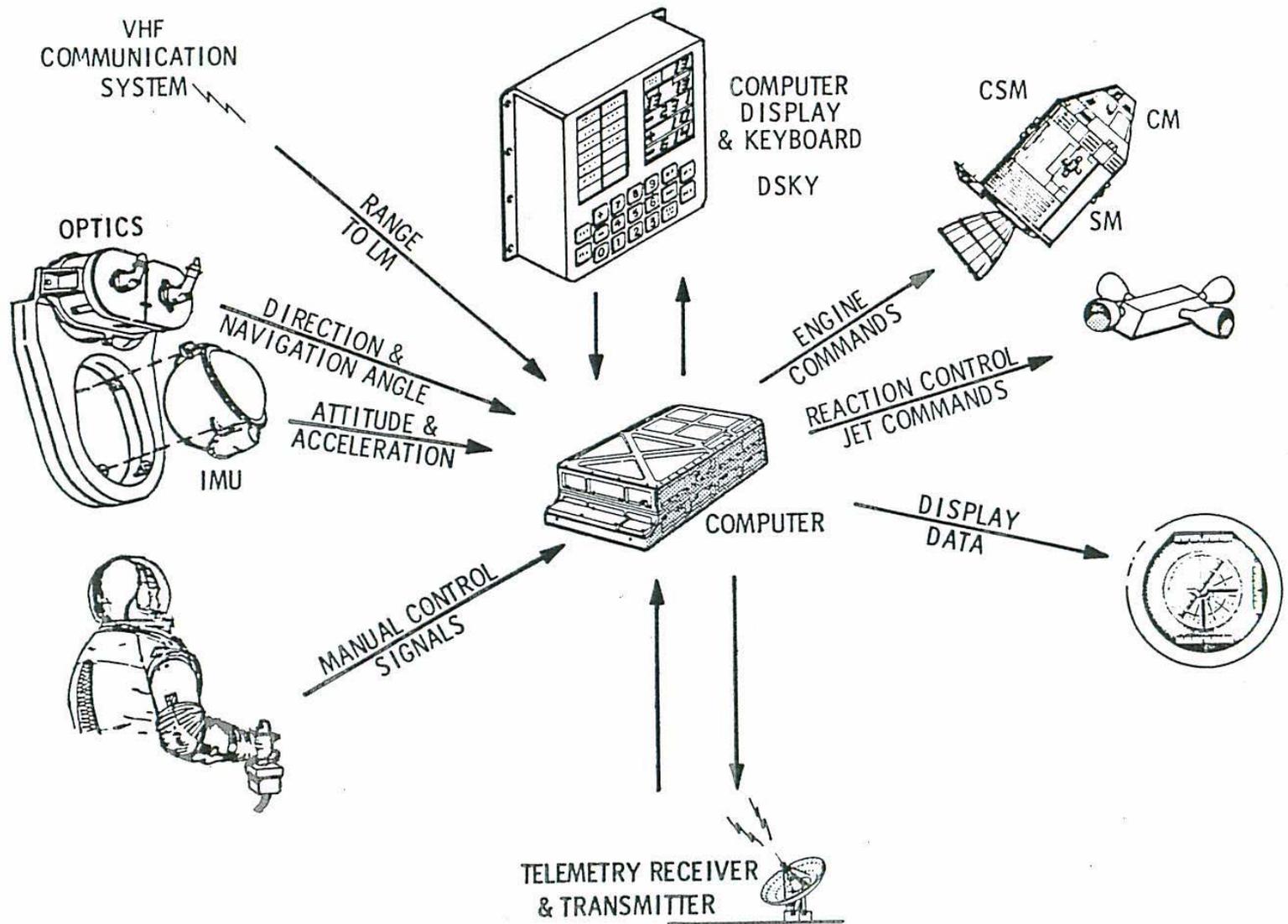


Apollo Spacecraft in Docked Configuration

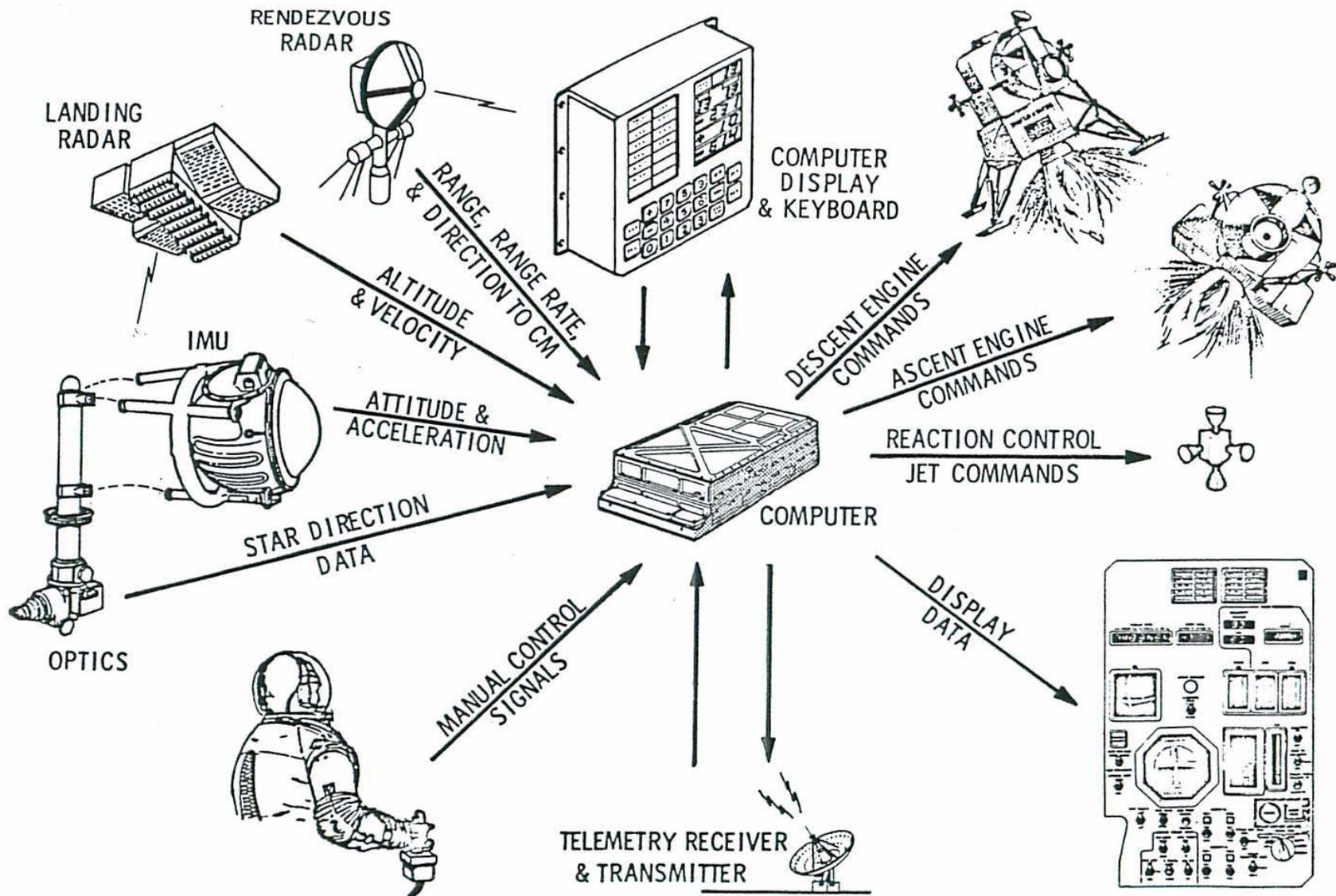


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Lunar Landing Mission Phases



Command Module Navigation Guidance & Control System Components



Lunar Module Navigation Guidance & Control System Components

Apollo Development Flights

	<u>Launch Date</u>	<u>Launch Vehicle</u>		<u>Mission</u>
Apollo 3 CSM	25 Aug 1966	AS-202	Unmanned	Ballistic Suborbital
Apollo 4 CSM	9 Nov 1967	AS-501	Unmanned	Orbital, High Apogee, Simulated Lunar Return
Apollo 5 LM	22 Jan 1968	AS-204	Unmanned	Lunar Module Earth Orbital
Apollo 6 CSM	4 Apr 1968	AS-502	Unmanned	Orbital, High Apogee Simulated Lunar Return
Apollo 7 CSM	11 Oct 1968	AS-205	Schirra, Eisele Cunningham	First Manned Earth Orbit
Apollo 8 CSM	21 Dec 1968	AS-503	Borman, Lovell Anders	Manned Lunar Orbit
Apollo 9 CSM/LM	3 Mar 1968 ¹⁹⁶⁹	AS-504	McDivitt, Scott Schweickart	First Manned LM Earth Orbit
Apollo 10* CSM/LM	May 1969	AS-505	Stafford, Young Cernan	LM Operations Lunar Orbit - No Landing
Apollo 11* CSM/LM	July 1969	AS-506	Armstrong, Collins, Aldrin	First Lunar Landing

A DYNAMICS CHALLENGE -- APOLLO BARBEQUE MODE

Requirement: For long periods of coasting flight, provide passive thermal control by implementing a "barbeque mode" -- a very slow rotation (one revolution per ten minutes or slower) about the spacecraft roll axis and with the desired roll axis direction fixed in space.

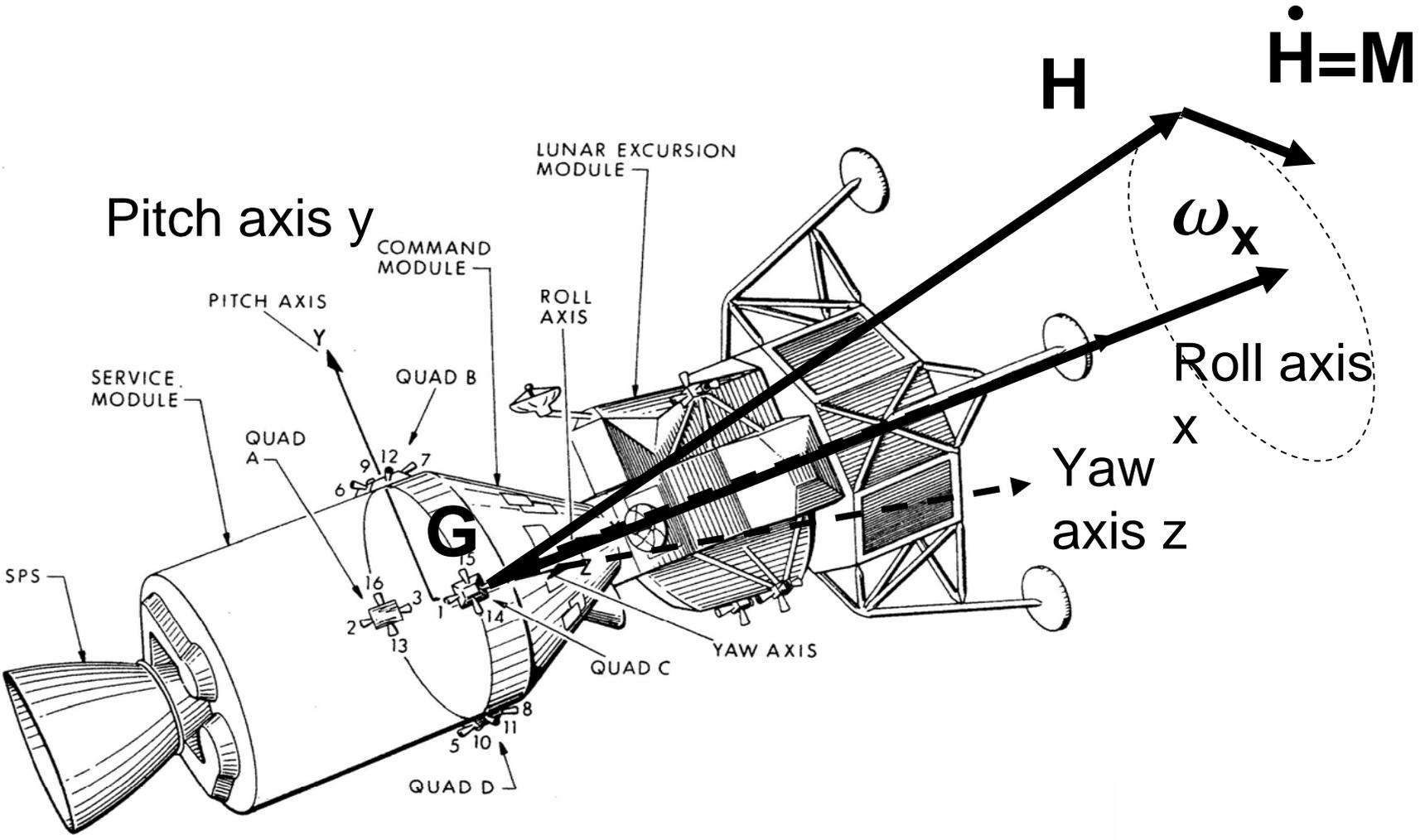
Design provided: An attitude control mode that used the reaction control jets to establish the initial desired angular velocity, and then as needed to maintain the spacecraft attitude close to the rotating desired attitude associated with the desired constant angular velocity vector along the roll axis with a fixed direction in space.

In-Flight Performance: There was a slight dynamic imbalance because the moment of inertia principal axes were not precisely aligned with the spacecraft axes. Active torquing was required to maintain the spacecraft attitude close to the desired rotating attitude. While the fuel consumption was thought to be acceptable, nevertheless the astronauts complained that the banging of a jet every minute or so made it impossible for them to sleep. NASA asked us at M.I.T. what to do?

First suggestion: Our first suggestion was to turn off the active automatic attitude control (no jet firings) after the initial desired angular velocity was established. It was hoped that the subsequent free-body motion would be reasonably close to the desired spinning motion. The astronauts gave this a try, but the subsequent wandering of the roll axis away from its desired azimuth and elevation were deemed too large. What else to try?

Second suggestion: Bill Widnall suggested that what was needed was to get the angular momentum vector much closer to the principal axis nearest to the roll axis and that this could be accomplished by not using the active attitude control mode to establish a precise roll angular velocity but rather by using the rotational hand controller to command a pure torque about the roll axis. The induced angular momentum vector would be aligned with that torque impulse. This worked very well. In the subsequent free-body motion the roll axis deviation away from its desired orientation was acceptably small and the astronauts got their sleep.

Active torquing required to have spacecraft roll axis remain aligned with desired angular velocity vector, which is fixed in space



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Apollo Spacecraft

Differential equations to simulate spacecraft free-body motion

Case 1 - Initially only roll angular velocity is non-zero (1 rev / 10 min)

Case 2 - Initial conditions are established by a roll axis torque impulse

$$\begin{matrix} \omega_x \\ \omega_y \\ \omega_z \end{matrix} \quad \frac{d}{dt} \omega = I^{-1} [\cancel{\tau} - \omega \times I \omega]$$

body

bank
elevation
azimuth

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

$$I = \begin{bmatrix} 75619 & 10413 & 11211 \\ 10413 & 712,171 & -5023 \\ 11211 & -5023 & 715,545 \end{bmatrix} \text{ kg m}^2$$

Initial conditions

$$\phi = \theta = \psi = 0$$

Case 1

$$\omega_x = 1.047 \times 10^{-2} \text{ rad/sec}$$

$$\omega_y = 0$$

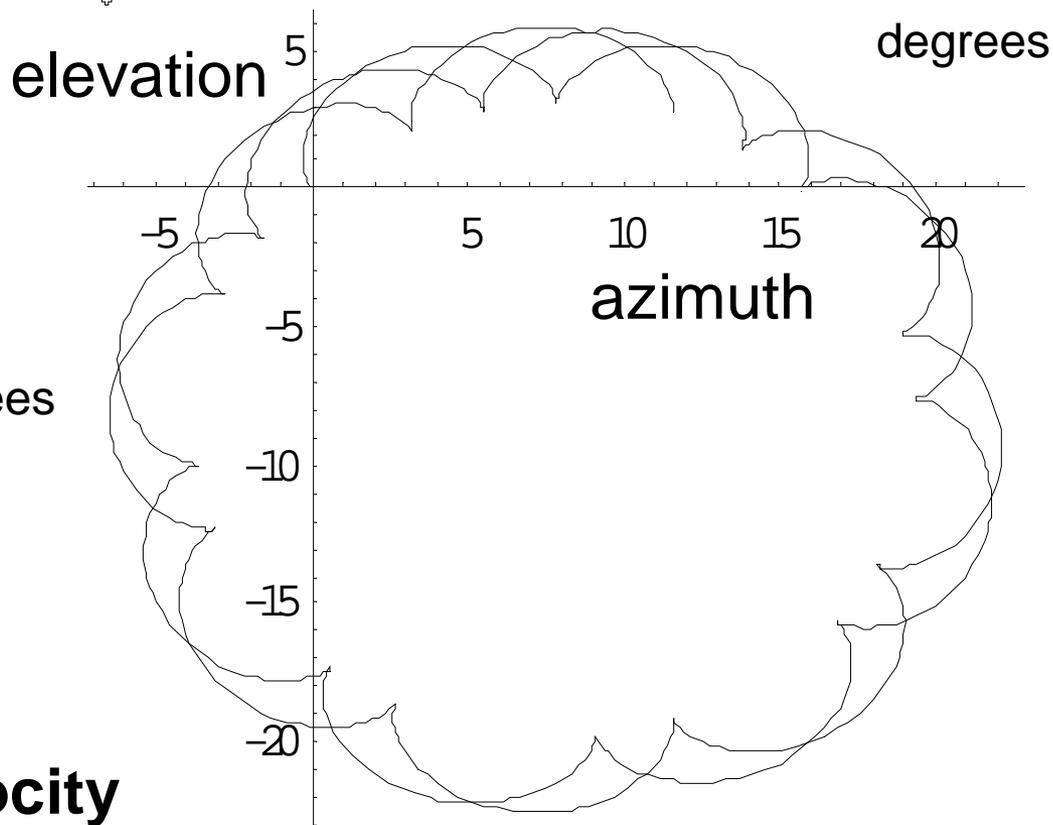
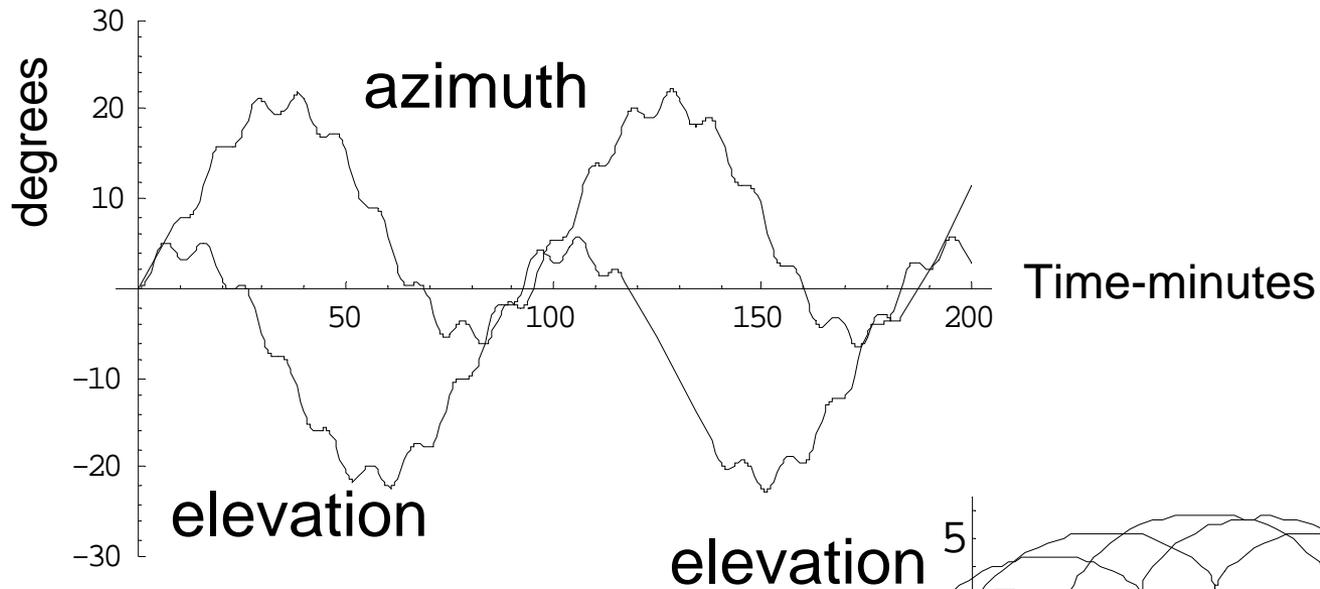
$$\omega_z = 0$$

Case 2

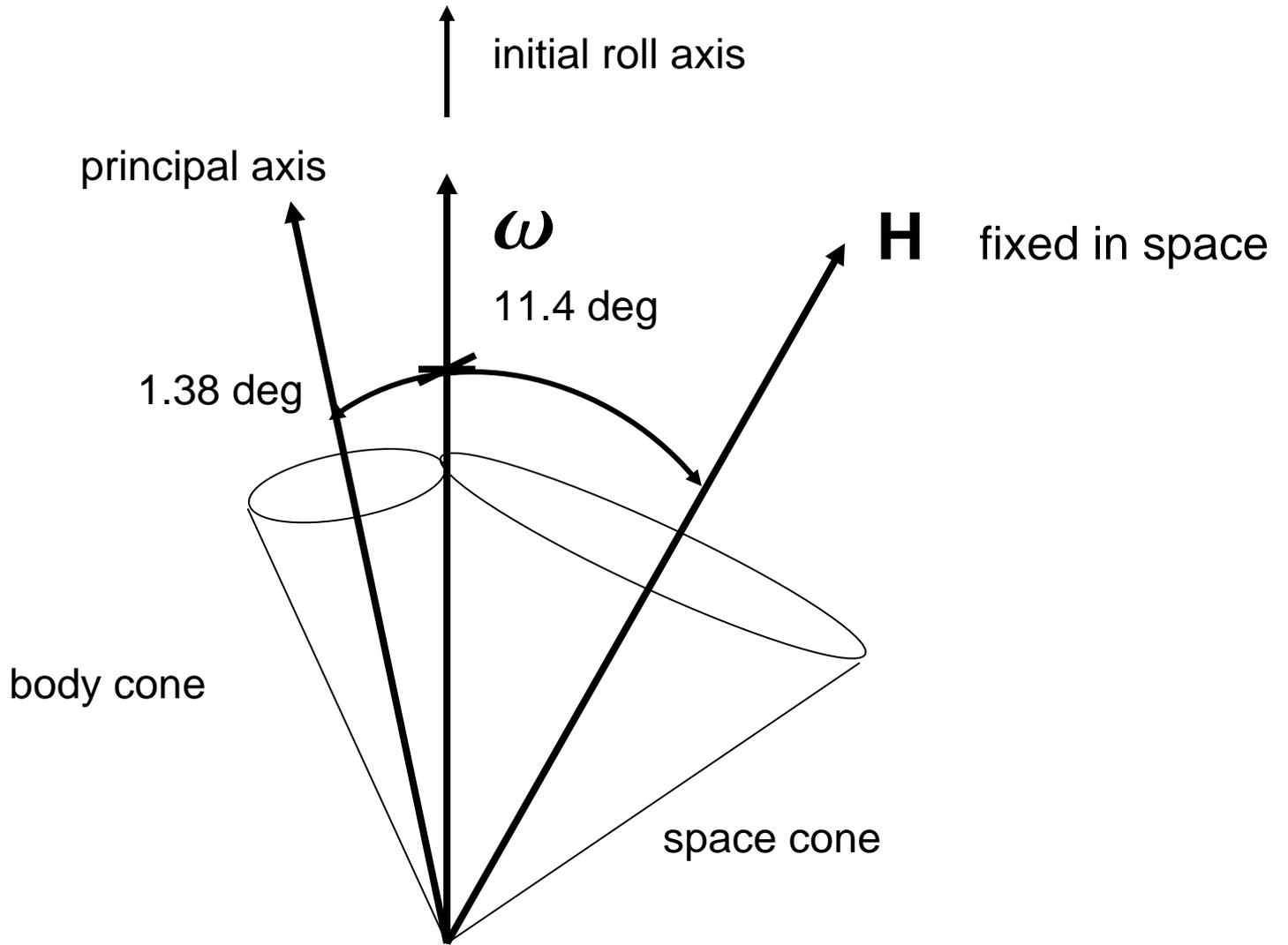
$$\omega_x = 1.047 \times 10^{-2} \text{ rad/sec}$$

$$\omega_y = -1.5425 \times 10^{-4}$$

$$\omega_z = -1.6512 \times 10^{-4}$$

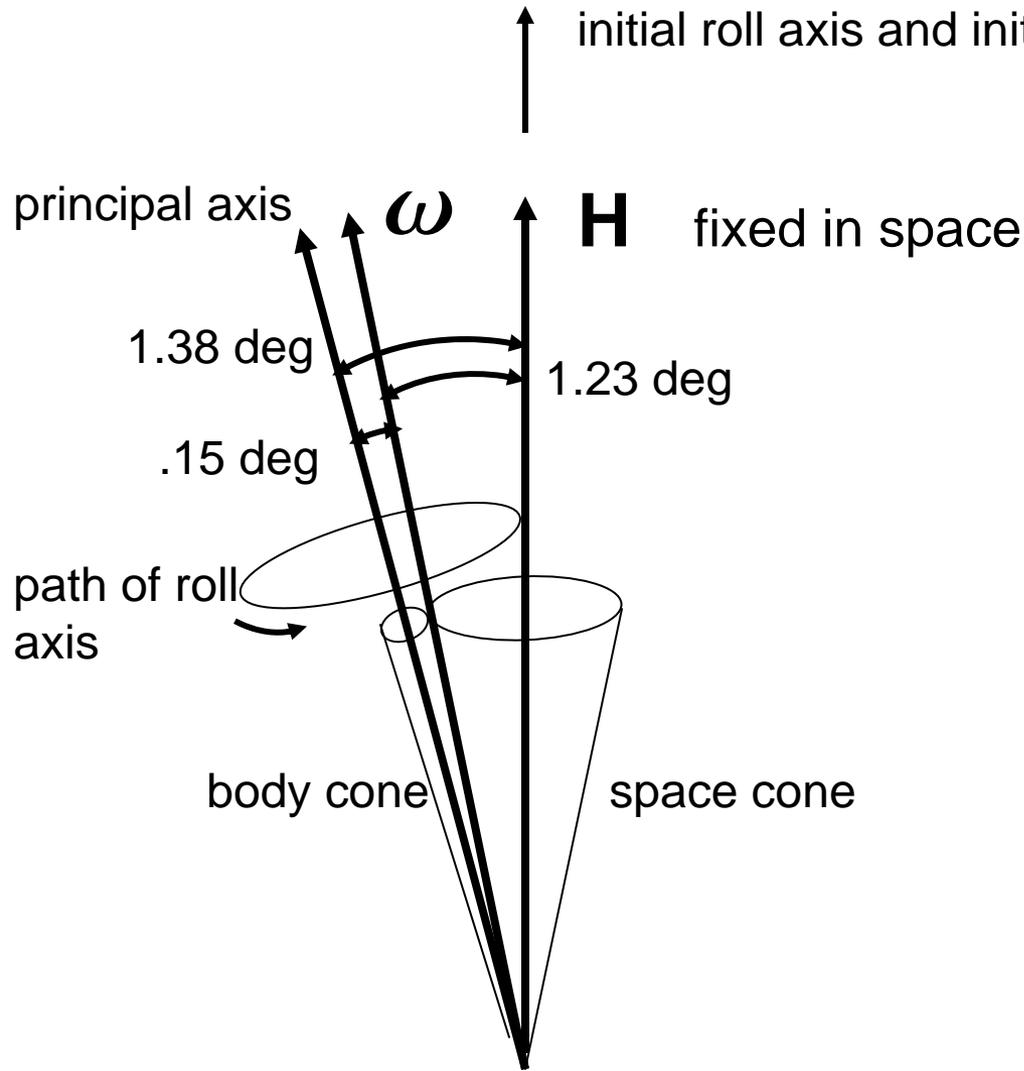


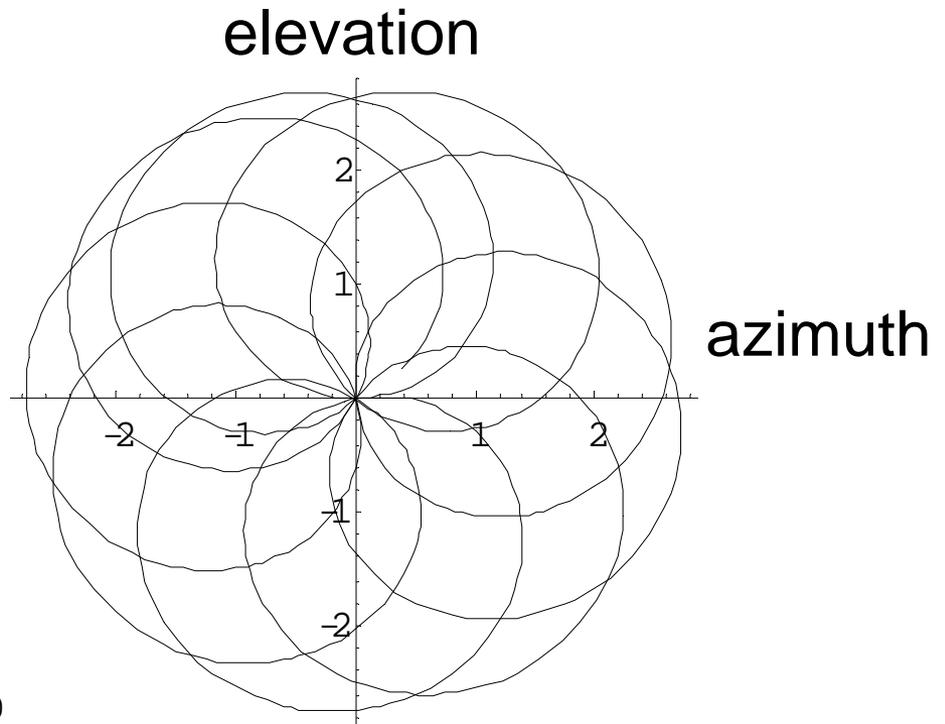
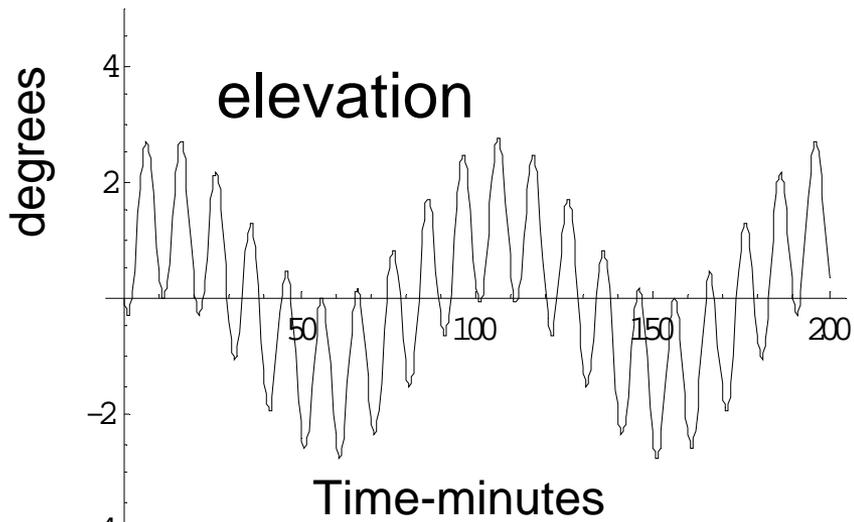
**Free-body motion of
spacecraft roll axis after
establishing angular velocity
solely along the roll axis**



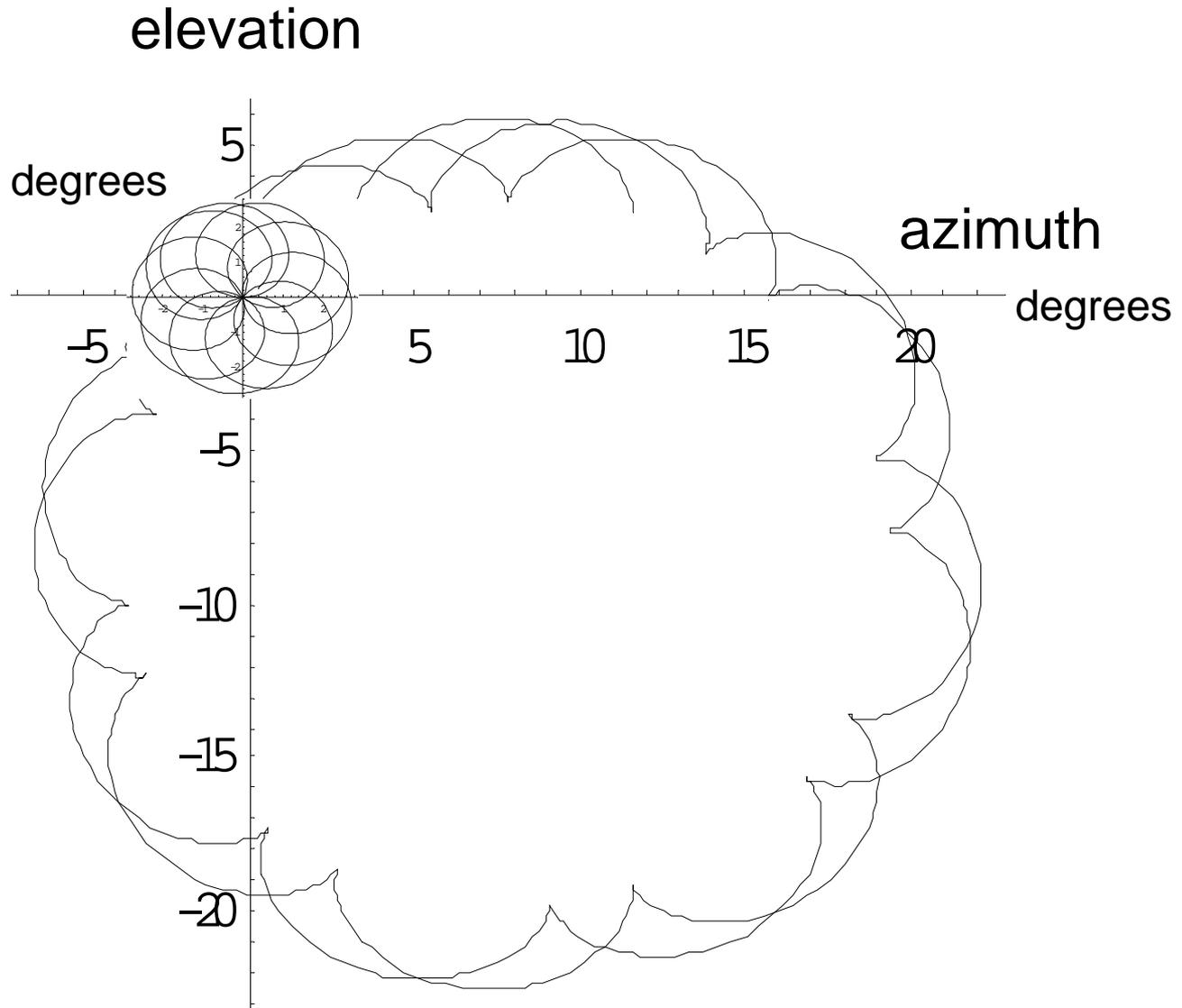
Free-body motion with initial ω parallel to roll axis is very close to that predicted when the two largest principal moments of inertia are equal

Free-body motion due to torque impulse applied about roll axis





**Free-body motion of spacecraft roll axis
after applying torque impulse about the roll axis**



Comparison of free-body motions of spacecraft roll axis for the two cases: angular velocity initial condition versus torque impulse initial condition

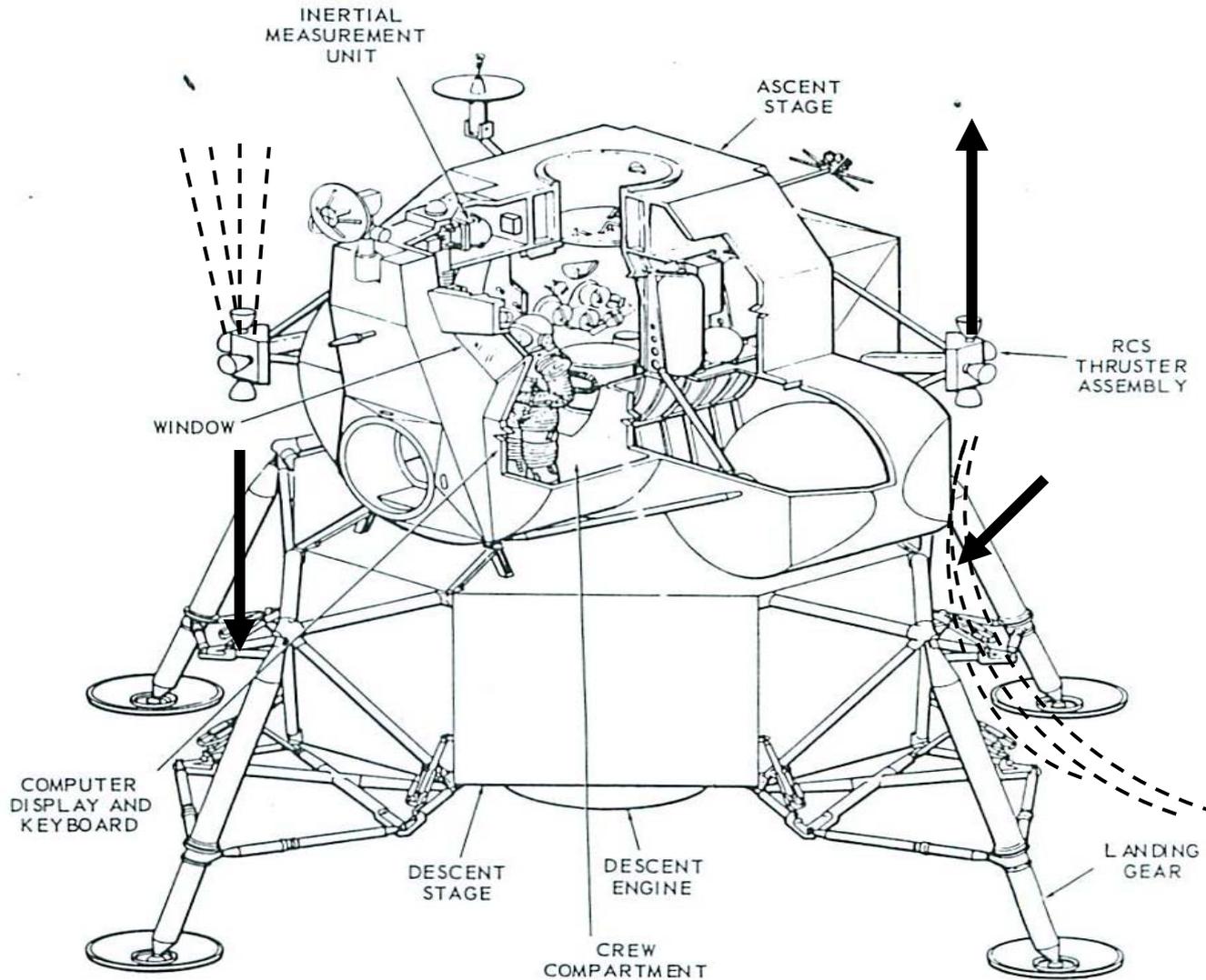
A "BACKUP" CONTROL MODE THAT HELPED SAVE LIVES -- USING THE LUNAR MODULE TO PUSH THE COMMAND MODULE

Requirement: Provide a capability for the Lunar Module to push the Command and Service Module, in case the CSM were to become disabled.

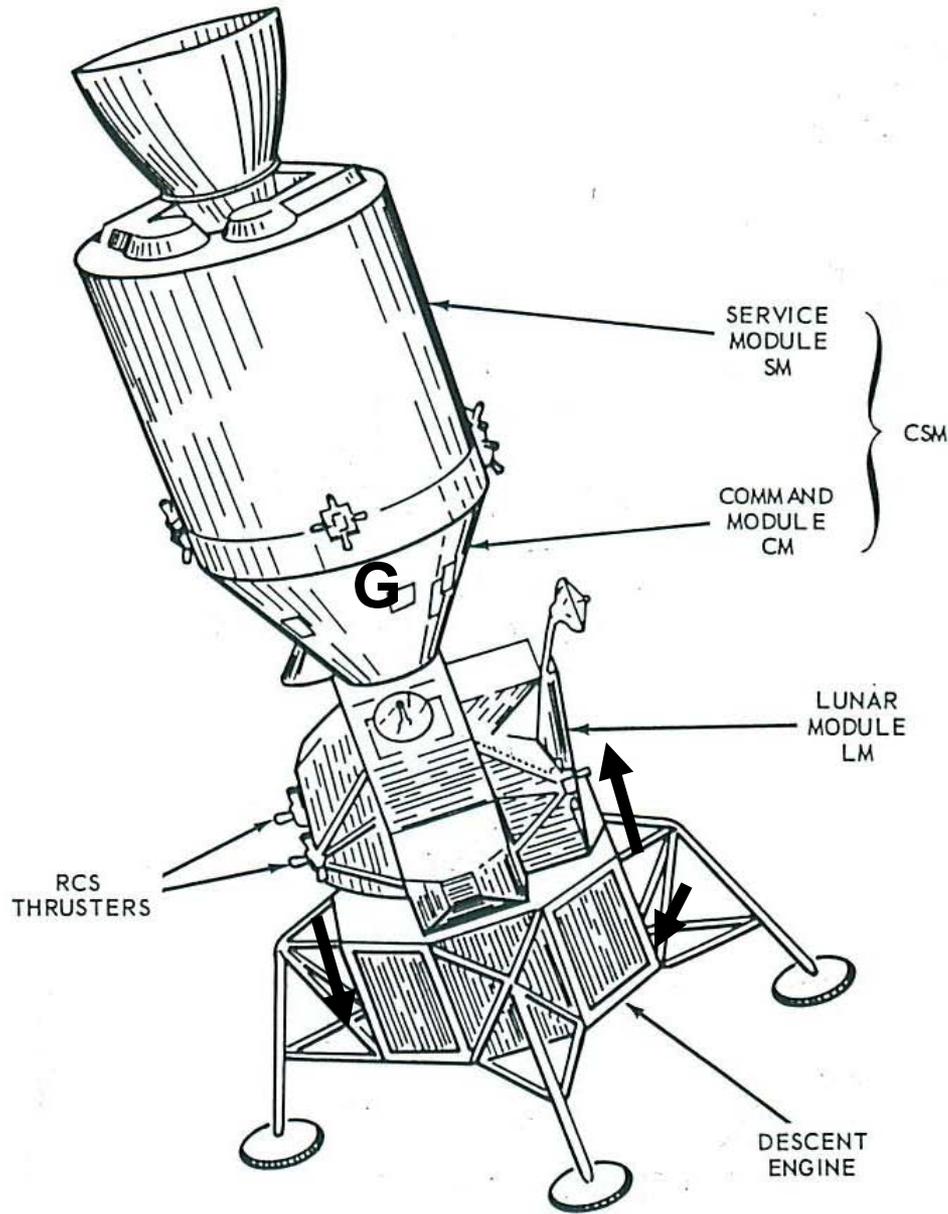
Challenges: The LM was not specifically designed to accommodate this requirement. When in the docked configuration, the LM reaction control jets had exhaust impingement problems: To use the jets that exhausted upward against the attached command module was not acceptable. The downward exhausting jets were known to impinge against the LM descent stage and this would produce significant adverse torque because of the more distant center of mass location.

Design approach: During powered flight use the thrusting LM descent-stage engine, rather than the reaction control jets, to control the spacecraft pitch and yaw. There was an engine gimbaling capability that could change the engine thrusting angles in the pitch and yaw planes at a very slow rate of 0.2 deg / sec . The initial intended use of this capability was to null out any pitch and yaw torques so that reaction jets would not have to be used continually to balance the bias torques. Bill Widnall proposed that it might be possible to do spacecraft pitch and yaw attitude control using this slow gimbaling capability of the descent engine. Because the gimbal rates were so slow, Widnall sought and successfully derived the minimum time optimal control law for the third-order dynamic systems in the two (pitch and yaw) planes. Simulation results indicated that this LM nonlinear minimum-time thrust-vector control law would be able to control the docked configuration in pitch and yaw without assistance from the reaction control jets.

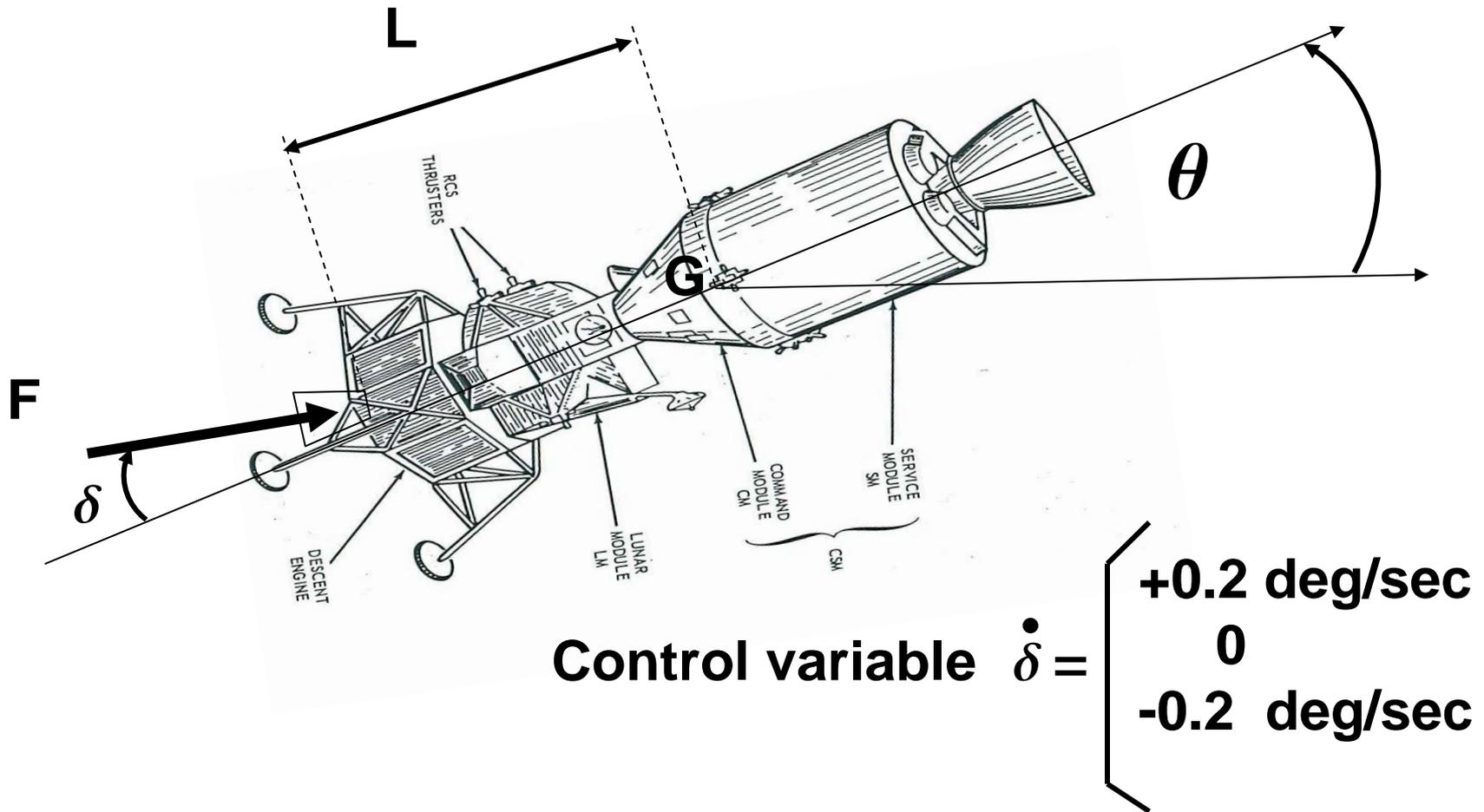
Apollo 13: On the way to the moon during the Apollo 13 mission, an explosion in the Service Module disabled the Service Module including its main engine. The lunar landing goal was aborted and the challenge became, could we get the astronauts home? Many things had to work, including the using of the undamaged LM to push the spacecraft when trajectory corrections were needed to maintain the free-return-to-earth trajectory. Fortunately the M.I.T. team had provided the backup control capability that now was needed. The astronauts were returned safely to earth



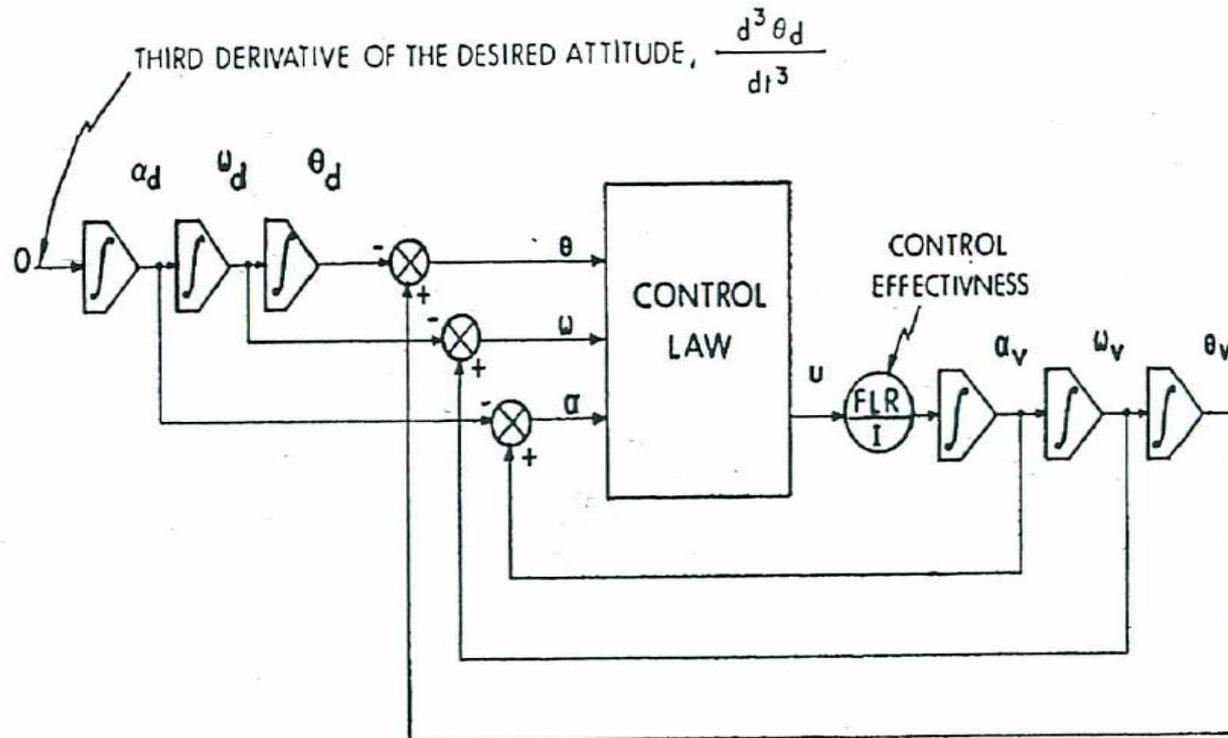
Descent Configuration of the Lunar Module: Reaction Control jet exhaust impingement weakens the applied torque



With the longer moment arm in the docked configuration the impingement force exerts a significant adverse torque

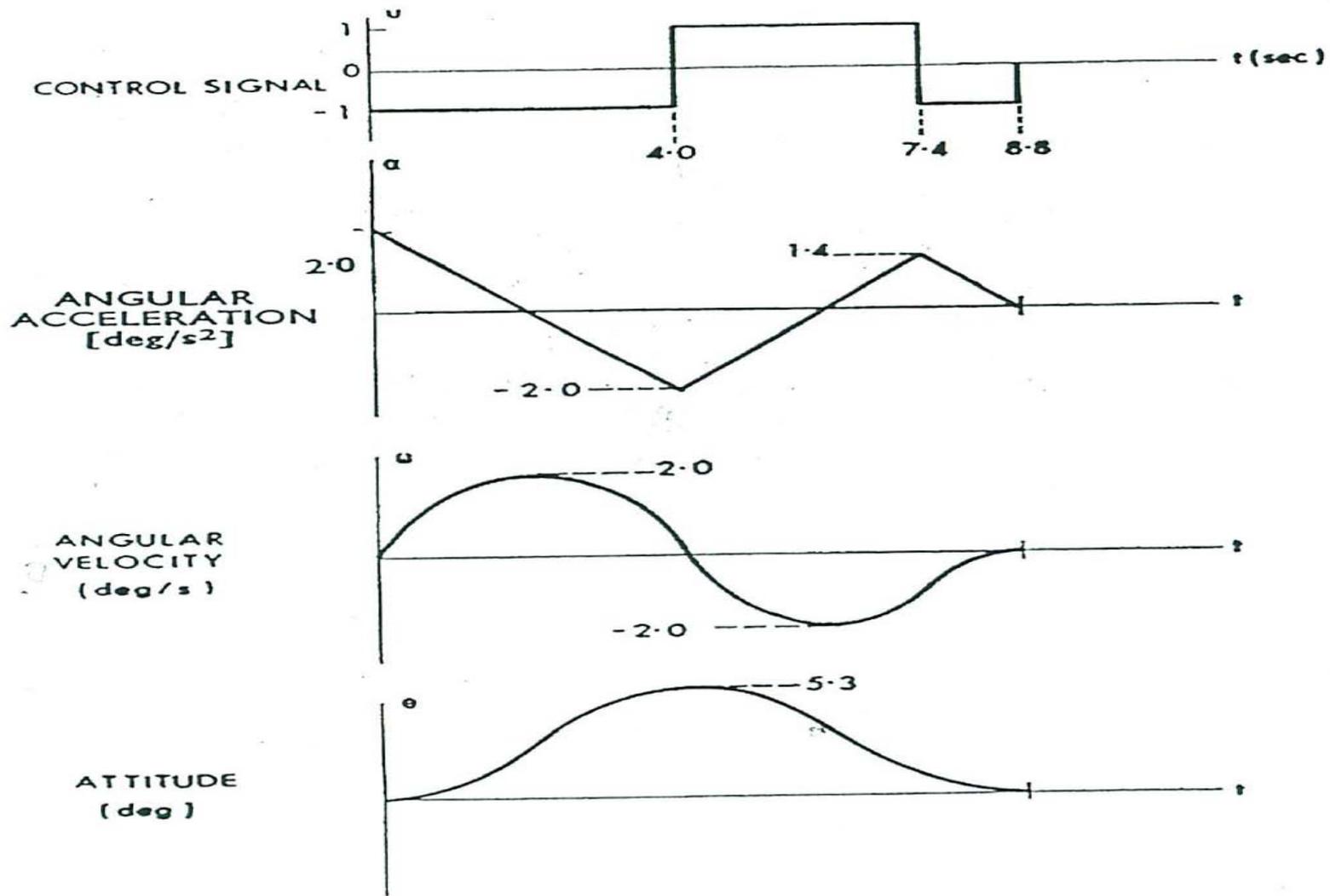


Thrust vector control of the docked configuration using the LM descent engine



- ω_v — VEHICLE ANGULAR VELOCITY
- α_v — VEHICLE ANGULAR ACCELERATION
- ω_d — DESIRED ANGULAR VELOCITY OF THE VEHICLE
- α_d — DESIRED ANGULAR ACCELERATION OF THE VEHICLE

The dynamics in the pitch or yaw plane is that of a triple-integral plant.



**Example of minimum time attitude control:
Response to an initial thrust misalignment at ignition**

$$c = \left(\frac{I}{FLR} \right)^{\frac{1}{3}}$$

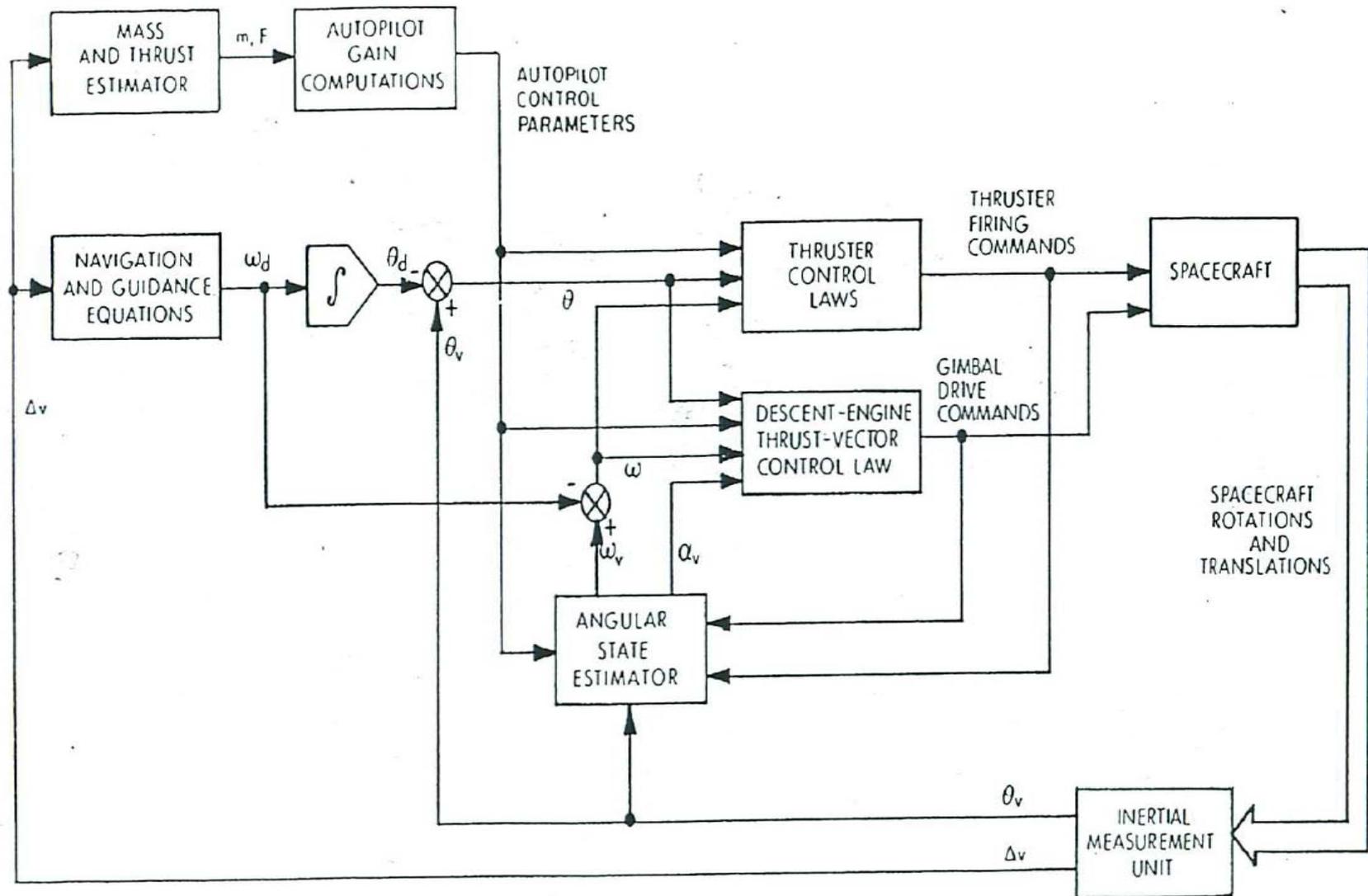
$$x_1 = c^2 \alpha, \quad x_2 = c \omega, \quad x_3 = \theta$$

$$s_1 = \text{sign}(x_1)$$

$$s_2 = \text{sign}\left(x_2 + \frac{1}{2}s_1 x_1^2\right)$$

$$u_{\text{opt}} = -\text{sign}\left[x_3 + \frac{1}{3}x_1^3 + s_2 x_1 x_2 + s_2 \left(s_2 x_2 + \frac{1}{2}x_1^2\right)^{\frac{3}{2}}\right].$$

The minimum-time thrust-vector control law in the LM digital autopilot



Information flow in the LM digital autopilot during descent engine powered flight

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