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A HYBRID SIMULATION FOR DYNAMIC VERIFICATION OF  
SATURN GUIDANCE AND CONTROL SUBSYSTEMS

by

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## I. INTRODUCTION

This paper presents a discussion of a hybrid simulation used to dynamically verify the Saturn Guidance and Control subsystems. First, the Saturn vehicle is briefly described to provide background information. The Instrument Unit (IU) is considered in more detail to give a proper setting for the Guidance and Flight Control (G and FC) discussion that follows. After a brief description of the actual G and FC System operation, simulation models of the G and FC components are considered in detail. This is followed by a discussion of the model assignment to a particular computer (digital or analog) and justification for making that assignment. Finally, results of the AS-204/LM1 hybrid simulation studies are briefly considered with mention of the actual flight data.<sup>1</sup>

## II. SATURN VEHICLE DESCRIPTION

The Saturn IB, which has two propulsive stages (Slide 1), is serving as a launch vehicle for the Apollo spacecraft earth orbital flight tests. These flights simulate certain studies of the lunar landing mission and provide flight

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<sup>1</sup> Some of the material in this paper is based on notes from an IBM conference presentation entitled, "Digital Computer Program for Support of Hybrid Computer Simulation of Saturn Launch Vehicle," by E. W. Snyder.

tests for the spacecraft and the S-IVB/IU Stage. Each Saturn IB has a payload consisting of some combination of a Lunar Module (LM), Service Module (SM), Command Module (CM), and Launch Escape System (LES).

The Saturn V, which has three stages (Slide 1), is the launch vehicle for the actual lunar landing missions. For these missions the Saturn V will carry a payload consisting of an LM, SM, CM, and LES.

### III. INSTRUMENT UNIT

The major purpose of the Instrument Unit (IU) shown in Slide 2 is to provide the Saturn vehicle with a centralized astronics package for guidance, control, sequencing, and telemetry during boost and earth orbit, and through lunar trajectory insertion. The IU subsystems (Slide 3) include the Structural Portion, Guidance, Flight Control, Environmental, Instrumentation, and Electrical.

#### A. Guidance and Flight Control Subsystems

Slide 4 lists the major components of the Guidance and Flight Control Subsystems. Included are the Launch Vehicle Digital Computer (LVDC), the Flight Control Computer (FCC), the ST-124 Inertial Platform, and the control accelerometer and rate gyro / control signal processor.

Slide 5 shows a rough sketch depicting the closed loop operation of the Guidance and Flight Control Subsystems. Sensors on the inertial platform measure the angles ( $\theta$ ) between the inertial and body reference frames and changes in velocity along each inertial axis. These signals are transmitted to the LVDC-LVDA where the velocities are used in navigation and in computing the commanded gimbal angles ( $\mathbf{x}$ ). The actual platform gimbal angles ( $\theta$ ) are differenced with the  $\mathbf{x}$ 's to give attitude error signals ( $\psi$ ) in the inertial platform frame. These  $\psi$ 's are transformed to result in attitude error signals ( $\Delta\phi$ ) in the body frame, which are fed to the FCC where they are filtered and summed with the filtered rate gyro signals ( $\dot{\phi}$ ) to give engine actuator commands ( $\beta_c$ ). The  $\beta_c$  signals drive the actuators and thus change the thrust vector orientation which in turn changes the vehicle attitude.

### IV. DYNAMIC VERIFICATION OF THE GUIDANCE AND CONTROL SYSTEM

Filters in the FCC and parameters in the LVDC flight program are designed to give satisfactory stability margins while maintaining good vehicle

response to guidance commands. These designs are determined by using linearized models and linear stability analysis techniques at a few frozen points in time. While this method of design has proved, thus far, to be reliable, it does not consider the effects of nonlinearities in the guidance system, nor does it consider vehicle dynamics continuously throughout boost flight. Thus, a means of dynamically checking the FCC filter design and LVDC flight program in a total system configuration under flight conditions, over all times of vehicle boost flight, was needed to ensure the nonexistence of adverse dynamic effects on the vehicle, the astronauts, and the guidance accuracy. It was decided that a system would be devised in which, except for the LVDC flight program, all components significantly affecting the vehicle dynamics would be simulated. For this task, a six degree-of-freedom real time hybrid simulation with LVDC/LVDA flight hardware in the loop was chosen that would fully exercise the flight program and check its dynamic effects on the vehicle throughout simulated boost flight, and at the same time check the FCC filter design for vehicle stability and response.

## V. HYBRID SIMULATION

Slide 6 shows a simplified G & FC loop for pitch and yaw. The LVDC and LVDA are flight-type hardware, while the Flight Control Computer, Engine Actuator, Vehicle Dynamics, Rate Gyro, Inertial Platform Assembly, and Propellant Utilization System (PU) are simulated on the hybrid system. Each component that significantly contributes to vehicle dynamics is described below, followed by a description of the simulation model of each component.

### A. Launch Vehicle Digital Computer (LVDC)

#### 1. Actual LVDC

Slide 7 depicts the Saturn V flight computer (LVDC) tasks by phase:

Phase I includes the time of first stage boost. During this phase the vehicle is moving through the dense portion of the atmosphere where high aerodynamic pressure occurs. To avoid excessive structural loads caused by guidance maneuvers, no guidance constraints are applied. An open loop guidance scheme in the form of a time tilt program is used.

Phase II includes the second stage boost time. The flight program during this phase uses a path adaptive guidance scheme called Iterative

Guidance Mode (IGM) in which guidance is a function of space-fixed position ( $\bar{r}$ ) and velocity ( $\dot{\bar{r}}$ ), F/m and time. This adaptive guidance scheme seeks to attain predetermined space-fixed position and velocity vectors with the consumption of a minimum amount of propellant.

Phase III includes the first burn time of third stage boost and orbital time. IGM guidance is used during the boost portion of this phase.

Phase IV includes the second burn time of third stage boost. IGM guidance is also used during this phase.

Phase V includes all mission time after S-IVB/IU Apollo Spacecraft separation.

The LVDC/LVDA has as inputs inertial platform gimbals angles, measured changes in velocity along each platform axis, and flight sequencing discrettes. The LVDC/LVDA outputs are attitude-error steering commands and flight sequencing discrettes.

Since an actual flight type LVDC/LVDA is used in the simulation, no LVDC/LVDA model was devised.

## B. ST-124 Inertial Platform Assembly

### 1. Actual Platform

The Inertial Platform Assembly (Slide 6) is the main sensor for guidance. At guidance reference release, which occurs a few seconds before liftoff, the platform becomes inertial (space-fixed). A resolver attached to each platform surface measures the gimbal angle ( $\theta$ ) between the surface and vehicle axis. These resolver outputs are read by the LVDC flight program every 40 milliseconds.

Integrating accelerometers, mounted along each axis of the platform, sense changes in measured velocities ( $\Delta \dot{X}_m$ ,  $\Delta \dot{Y}_m$ ,  $\Delta \dot{Z}_m$ ) in increments of .05 m/sec. Signals representing these velocity changes automatically increment or decrement velocity counters in the LVDA. These counters are read periodically by the LVDC flight program.

## 2. Platform Simulation Model

Platform gimbal angles ( $\theta$ ) are simulated by first transforming the simulated body rates ( $\dot{\phi}$ ) (Slide 6) into the inertial coordinate frame, and then integrating the resulting gimbal angle rates ( $\dot{\theta}$ ). Gimbal angles are computed and transmitted to the LVDA at a 40-millisecond rate.

The platform integrating accelerometers are simulated in two ways: During first stage simulation, vehicle thrust is obtained through a table lookup scheme of thrust versus vehicle altitude. Thrust is then used with remaining vehicle mass ( $m_v$ ), which is computed, to obtain total vehicle acceleration ( $F/m_v$ ). This acceleration is resolved through the simulated engine angles ( $\beta$ ) to result in body acceleration components ( $\ddot{X}_B, \ddot{Y}_B, \ddot{Z}_B$ ). which in turn are transformed via the platform gimbal angles ( $\theta$ ) into inertial platform acceleration components ( $\ddot{X}_m, \ddot{Y}_m, \ddot{Z}_m$ ). These accelerations are then used to compute changes in measured platform velocity components ( $\Delta\dot{X}_m, \Delta\dot{Y}_m, \Delta\dot{Z}_m$ ) which would normally be sensed by the platform integrating accelerometers. The measured velocity changes are computed and transmitted through special interface equipment to the LVDA every 40 milliseconds. During the second and third stage simulation, vehicle thrust is obtained through a table lookup scheme of thrust versus Propellant Utilization System (PU) valve position, which is the output of the PU System simulation model. After vehicle thrust has been obtained, changes in the platform-measured velocities ( $\Delta\dot{X}_m, \Delta\dot{Y}_m, \Delta\dot{Z}_m$ ) are derived in the same manner as in the first stage simulation.

### C. Flight Control Computer (FCC)

#### 1. Actual FCC

The primary functions of the FCC are to provide command signals ( $\beta_c$ ) to the engine actuators and to ensure adequate vehicle stability by compensating the guidance and control loop with proper attitude error and rate filters. These filters are implemented with passive elements.

The FCC shown in Slide 6 has as inputs attitude-error steering commands ( $\Delta\phi$ 's) from the LVDA and body rates ( $\dot{\phi}$ 's) from the body rate gyros. These inputs, when filtered in the FCC and summed, result in actuator commands ( $\beta_c$ 's) which move the engine actuator, and thus the thrust vector, to cause changes in vehicle dynamics.

## 2. FCC Simulation Model

Slide 8 shows a simplified block diagram of the pitch control loop, including sloshing and bending models for a single engine stage. The simulated attitude and attitude rate filters are implemented with passive elements as in the actual FCC. The control gains  $a_0$  and  $a_1$  are changed during actual and simulated flight in discrete steps to offset changes in the control moment of inertia.

### D. Engine Actuators

#### 1. Actual Actuators

The Saturn engine actuators, while differing in type from stage-to-stage, are all highly nonlinear with rate and position limits.

#### 2. Actuator Simulation Models

Linear approximations of the engine actuators are used in the hybrid simulation. The transfer functions for these actuator models are of order three or four, depending on the boost stage. In using these linear approximations, small engine angles (0 to  $\pm 3$  degrees) are assumed. Simplified nonlinear actuator models are presently being developed to handle more severe cases of engine movement.

### E. Body Bending Model

The effects of one mode of body bending, caused by forces due to engine position ( $\beta$ ) and acceleration ( $\ddot{\beta}$ ), are simulated in the pitch plane (Slide 8) by a second order linear model. The effects of bending ( $\dot{\phi}_B$  and  $\Delta\theta_B$ ) are sensed by the rate gyros and platform gimbals and therefore affect the guidance and control loop.

### F. Moment Equation Model

Motion of the rigid body is described by simple rotational mechanics: The attitude acceleration ( $\dot{\phi}$ ) is equal to a moment coefficient  $C_2$  times  $\sin \beta$ , where  $C_2$  is total thrust times the moment arm (distance from engine gimbal to center of gravity) divided by the moment of inertia. The Hybrid Simulation



computes  $C_2$  on line from its component parts. The small angle approximation  $\sin \beta = \beta$  (radians) is used.

#### G. Propellant Slosh Model

Propellant Sloshing (LOX and LH<sub>2</sub>) effects on the vehicle attitude acceleration in the pitch plane and the Propellant Utilization System Valve Control are included in the simulation of the second and third stages. The inputs that cause major sloshing action in the pitch plane are the vehicle translational acceleration due to thrust in the pitch plane and vehicle attitude acceleration in the pitch plane. These inputs cause the propellants to move against the tank walls which, in turn, causes attitude acceleration to be induced by two factors: the force of the propellant sloshing mass acting on tank walls through a moment arm about the center of gravity, and the sloshing mass being displaced from the center line of the vehicle acting through a radial moment arm about the center of gravity. The model used to simulate the sloshing effect during second and third stages consists of two linear second-order directly coupled differential equations with mass varying coefficients. These differential equations describe the radial motion of the slosh mass (LOX and LH<sub>2</sub>) in the pitch plane.

#### H. S-II and S-IVB Propellant Utilization Systems (PU)

##### 1. Actual PU System

One function of the PU system is to control the LOX and LH<sub>2</sub> flow to the thrust chamber in such a manner that depletion of LH<sub>2</sub> and LOX will occur simultaneously. Remaining LOX and LH<sub>2</sub> are measured by capacitance-type probes in each tank. The signal from each probe is gain adjusted so that when the two signals are differenced, a resulting signal will drive the PU valve position servo to give a desired EMR.

Sloshing (LH<sub>2</sub> and LOX) causes the signals representing remaining propellant to vary, which in turn tends to cause the PU valve position, EMR, and thrust to vary at the sloshing (LOX and LH<sub>2</sub>) frequencies. Since a varying thrust has ill effects on the guidance system, the PU valve control signal is filtered so that sloshing frequencies are highly attenuated in the resulting valve control signal.

## 2. PU Simulation Models

Slide 9 depicts a S-IVB PU system model obtained from a MSFC Guidance Dynamics Design Document.<sup>2</sup> This is basically the model used in the Hybrid Simulation. The S-II model is essentially the same except for a different sloshing filter. In the PU model, remaining LH<sub>2</sub> and LOX masses at any point in time are determined by integrating the total flow rates and subtracting these from the initial LH<sub>2</sub> and LOX masses. Slide 9 also shows how the effects of propellant sloshing on the PU system are implemented.

## VI. COMPUTING TASK ASSIGNMENTS

In assigning computing tasks several factors were considered that seemed to fall into two general categories as shown in Slide 10 and as follows:

### A. Application Orientation

#### 1. Frequency Content

In the Hybrid Simulation, models with high frequency content were simulated on the analog computer, which has a bandwidth of several kHz. The frequency response of digital computers depends on both the algorithms used to represent a given model and the solution rate of the algorithms. In general, for good accuracy, the solution rate must be several times the highest significant frequency.

#### 2. Precision Requirements

Where high precision was required the digital computer was used, because parameter value can be maintained and expressed in much smaller increments. An analog signal value is usually expressed in no more than four or five decimal places.

#### 3. System Composition

In the real world the LVDC is digital while the FCC is analog. Precision in a simulation need not be greater than it is in the actual system. This was a consideration in assigning the FCC simulation task.

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<sup>2</sup> MSFC Memo #R-ASTR-F-66-45, Phase II Guidance Dynamics Design Document for AS-207, 8 March 1966.

#### 4. Flight Hardware Interface

The output of the hardware (LVDC-LVDA) consists of attitude steering commands ( $\Delta\phi$ ) which are analog signals. The inputs to the flight hardware are platform velocity counts, which are discrete in nature, and platform gimbal angles, which are analog signals.

#### 5. Type of System

One important consideration in some of the model assignments was the time varying coefficients in the differential equations representing the models. The analog computer readily lends itself to modeling the differential equation while the digital computer easily handles time varying coefficients. The models were therefore simulated on a hybrid system using multiplying DAC's to combine the coefficients with the dependent variable and its derivatives.

#### B. Simulation Hardware

##### 1. Memory Size and Speed of Digital Computers

While memory size can be important, it was not a consideration in this simulation. The speed of the digital computer was a consideration, in that it determined how fast the various loops in the program could be processed and, therefore, what the solution rates for the various model algorithms would be.

##### 2. Equipment Configuration of the Analog Computer

Task assignment is largely dependent on the types and number of elements on the analog computer. In this simulation the analog computer specifications were based on the already determined task assignments listed below; thus the elements were not really a consideration in this case.

##### 3. Linkage Characteristics

The bit configuration (word length), conversion rates, and number of channels (D/A, A/D, D/D) were important considerations in assigning certain tasks.

#### 4. Communication Channel Count and Precision Versus Consolidation of Small Computing Task on One Machine

When implemented all-analog or all-digital by the use of special techniques, a model which is best suited to hybrid application will use fewer conversion channels but may lose precision and accuracy.

#### C. Assignments

Slide 11 shows a list of the actual computing task assignments. These are as follows:

- Analog
  - Flight Control Computer
  - Control Actuator
  - Moment Equations
  - Propellant Slosh Model
  - Body Bending Model
  - Propellant Utilization Control System
  
- Digital
  - Inertial Platform
  - Time and Mass Varying Function Generation
  - Navigation Model
  - Telemetry Ground Station
  - Control of Automated Setup and Checkout of Analog Computer
  - Propellant Utilization System Valve and Pump Model
  - Data Reduction and Preparation

#### D. Hybrid Simulation Tie-In

Tie-in of the total hybrid simulation is presented by tracing system signal flow in the S-IVB stage pitch plane as follows. The analog computer receives the attitude steering command ( $\Delta \phi_p$ ) from the LVDC-LVDA. The control computer model filters this signal and sums it with the filtered body attitude rate ( $\dot{\phi}_p$ ) generated by the vehicle dynamics model. The resulting signal ( $\beta_{cp}$ ) is fed to the actuator model which generates the simulated engine

angle ( $\beta_p$ ). This is then multiplied by the control moment coefficient ( $C_{2p}$ ), provided by a digital model, to result in a rigid body pitch attitude acceleration due to engine thrust. This component is summed with the attitude acceleration arising from propellant sloshing to give total attitude acceleration ( $\ddot{\phi}_p$ ). This  $\ddot{\phi}_p$  is integrated once to result in rigid body attitude rate ( $\dot{\phi}_p$ ) that is summed with attitude rate due to body bending ( $\dot{\phi}_{bp}$ ) to give a simulated body rate gyro output ( $\dot{\phi}_{gp}$ ). The propellant sloshing model has as inputs, engine angle ( $\beta_p$ ) and attitude acceleration ( $\beta_p$ ), while the bending model is forced by engine angle ( $\beta_p$ ) and engine rotational acceleration ( $\ddot{\beta}_p$ ).

The propellant utilization (PU) system is forced by remaining LOX and LH<sub>2</sub> mass which are computed on a digital computer. The PU system is perturbed by radial positions of propellant sloshing masses (LOX and LH<sub>2</sub>). The output of the PU system is valve position ( $\delta_v$ ).

A digital computer receives as inputs from the analog models the attitude rate ( $\dot{\phi}_{gp}$ ), the engine angle ( $\beta_p$ ), and the PU valve position ( $\delta_v$ ). The  $\dot{\phi}_{gp}$  is resolved into the inertial platform frame to result in a platform gimbal angle rate ( $\dot{\theta}_p$ ), which is integrated to give the gimbal angle ( $\theta_p$ ). The PU valve position ( $\delta_v$ ) is used in a table look scheme of total thrust (F) versus  $\delta_v$  to obtain F, which is then divided by remaining vehicle mass ( $m_v$ ) to result in total vehicle acceleration ( $F/m_v$ ). Vehicle mass is computed by subtracting integrated propellant flow rates from initial vehicle mass. Components of body acceleration are obtained by resolving  $F/m_v$  through the engine gimbal angles. These components are in turn resolved through the inertial platform gimbal angles to result in inertial platform accelerations components, which are used to compute changes in measured platform velocities. These changes in velocities and the simulated inertial platform gimbal angles are transmitted via special interface equipment to the LVDC-LVDA where the accumulated velocity changes are used for navigation and computation of commanded platform gimbal angles ( $\mathbf{x}$ ). These  $\mathbf{x}$ 's when differenced with the actual platform gimbal angles result in attitude error signals ( $\psi$ ) which are transformed into the body frame to result in attitude steering commands ( $\Delta\phi$ ). These  $\Delta\phi$ 's are then transmitted to the analog computer to close the guidance and control loop.

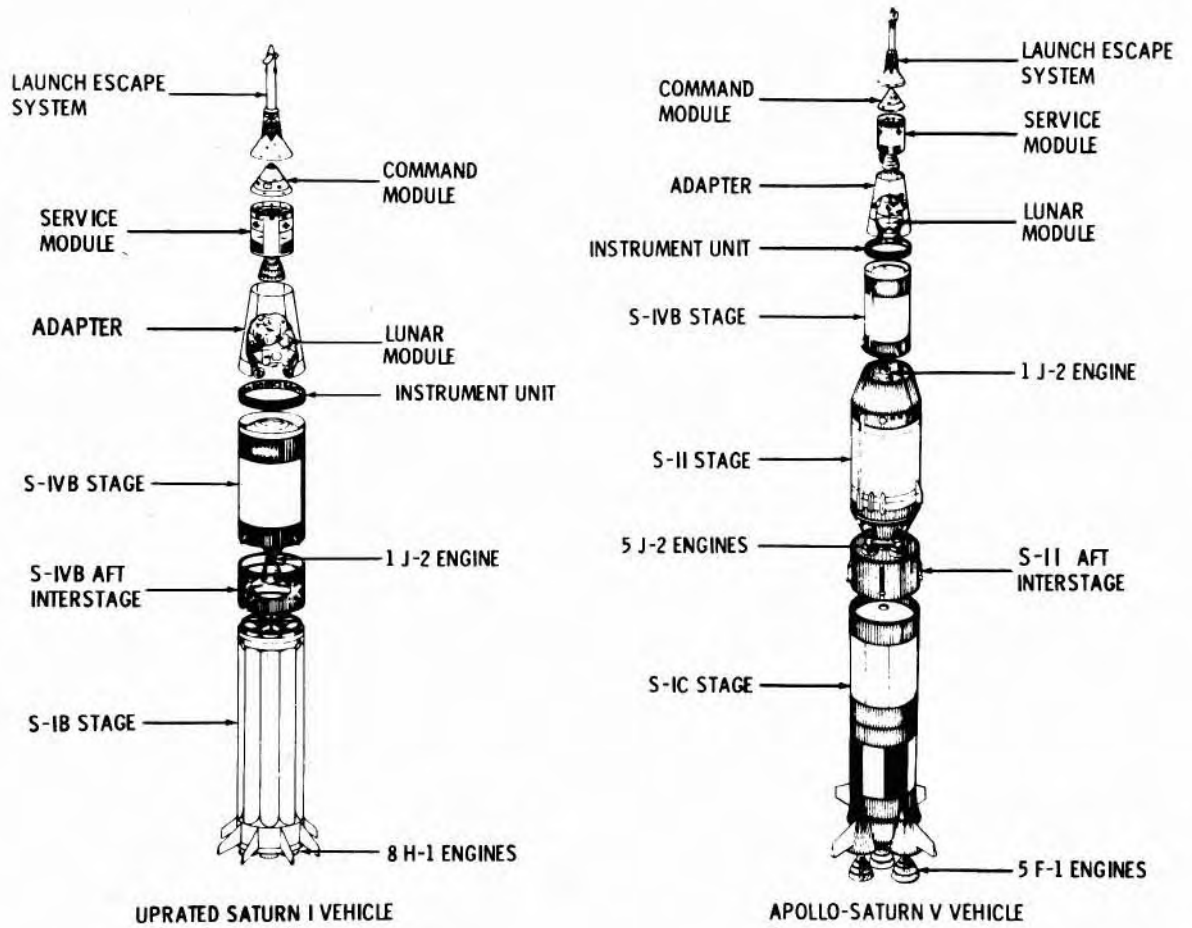
## VII. RESULTS

In concluding this presentation, some of the results from the AS-204 LM/1 Hybrid Simulation studies will be discussed. Slides 12 and 13 show strip recordings of some of the simulated vehicle and systems dynamics for a nominal case. From left to right on Slide 12 are the pitch attitude steering command ( $\Delta\phi_p$ ), pitch engine angles ( $\beta_p$  (1,2) and ( $\beta_p$  (3,4), pitch body rate ( $\dot{\phi}_p$ ), yaw attitude steering command ( $\Delta\phi_Y$ ), yaw engine angles ( $\beta_Y$  (2,3) and

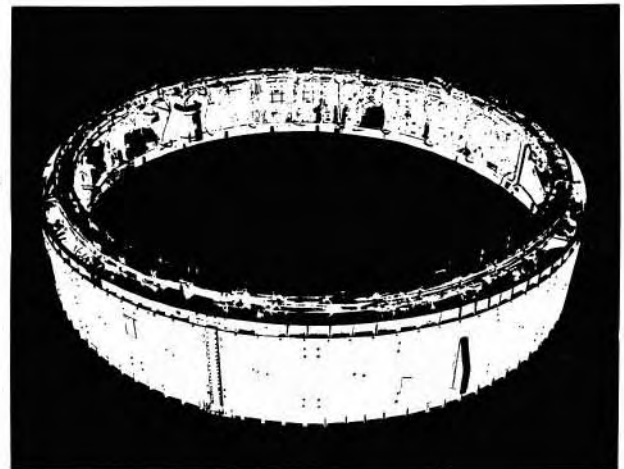
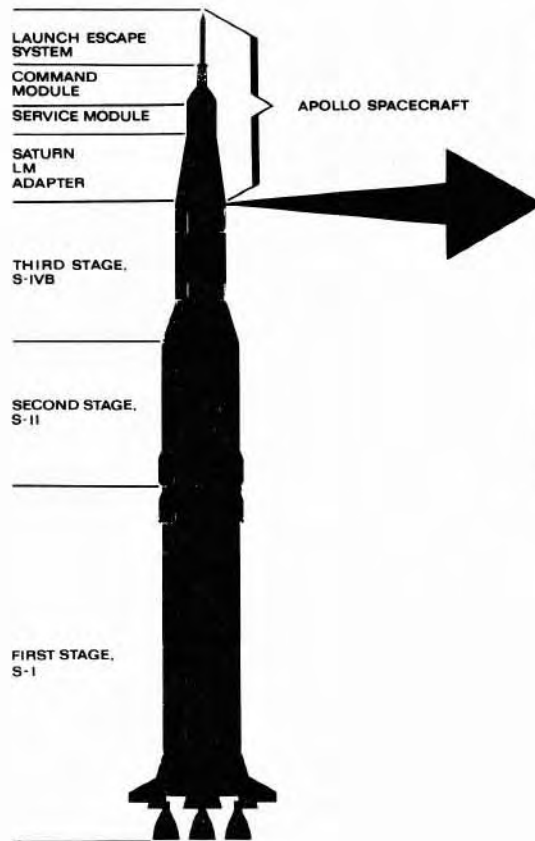
( $\beta_Y$  (1,4), and yaw body rate ( $\dot{\phi}_Y$ ). Magnitudes of these parameters and significant flight events are indicated. Slide 13 shows (from left to right) the roll attitude command ( $\Delta\phi_R$ ), body roll rate ( $\dot{\phi}_R$ ), radial displacement of the fuel and LOX sloshing mass ( $Z_F$  and  $Z_L$ ), remaining LOX and fuel weight ( $W_L$  and  $W_F$ ), the change in engine mixture ratio ( $\Delta EMR$ ), and PU valve position ( $\delta_V$ ). These simulation results compare favorably with actual flight data. All significant differences are attributable to uncertainties in certain initial conditions. While results from the hybrid simulation have been good, certain anomalies in actual Saturn flights have revealed a need for studies that were not previously considered. These studies can be handled by making slight modifications to certain simulation models.

## VIII. SUMMARY

A hybrid simulation is used to dynamically verify the guidance and control subsystems of Uprated Saturn I and Saturn V vehicles. This is done by simulating pertinent vehicle dynamics in a closed guidance and flight control loop with flight-type (LVDC and LVDA) hardware in the loop. In conjunction with equipment constraints, the computational complexity imposed by the requirements for high precision solutions of the guidance and navigation equations throughout the total boost portion of the mission and for accurate solution of nonlinear differential equations with variable coefficients and high frequency content led to the choice of a hybrid system for this application. This simulation has already proven to be a valuable tool for preflight prediction of vehicle/system dynamic performance and its effects on guidance accuracy. With further developments, it will also be useful for detailed evaluation of dynamic behavior under extreme combinations of off-nominal situations.



Slide 1



SATURN INSTRUMENT UNIT



# ***Instrument Unit Subsystems***

- STRUCTURAL PORTION
- GUIDANCE AND CONTROL
- ENVIRONMENTAL CONTROL
- MEASURING AND TELEMETRY
- RADIO FREQUENCY
- ELECTRICAL

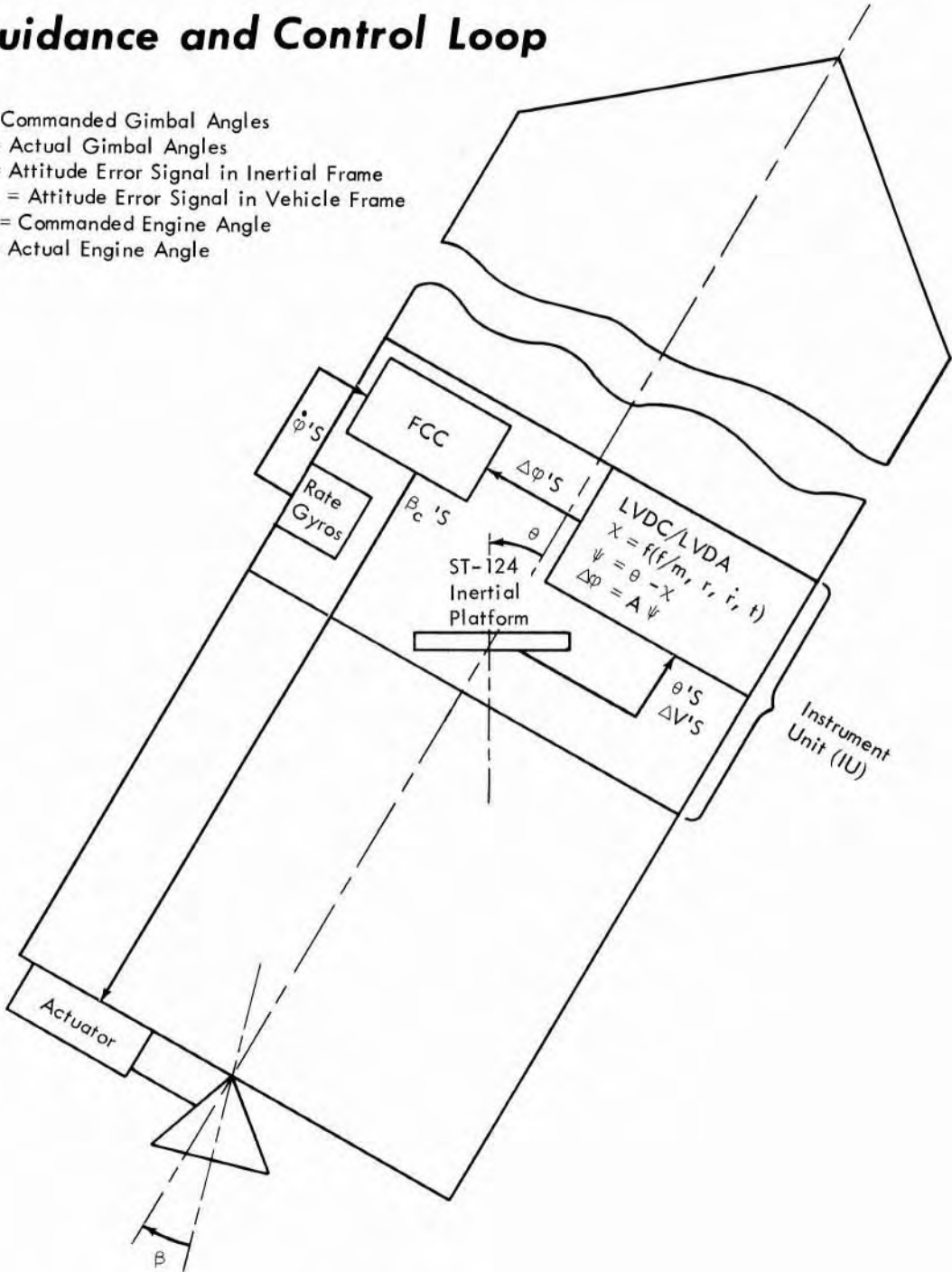
# ***Guidance and Control Subsystem***

- LAUNCH VEHICLE DIGITAL COMPUTER (LVDC)
- LAUNCH VEHICLE DATA ADAPTER (LVDA)
- FLIGHT CONTROL COMPUTER (FCC)
- ST 124 INERTIAL PLATFORM
- BODY RATE GYROS

# Simplified Saturn V

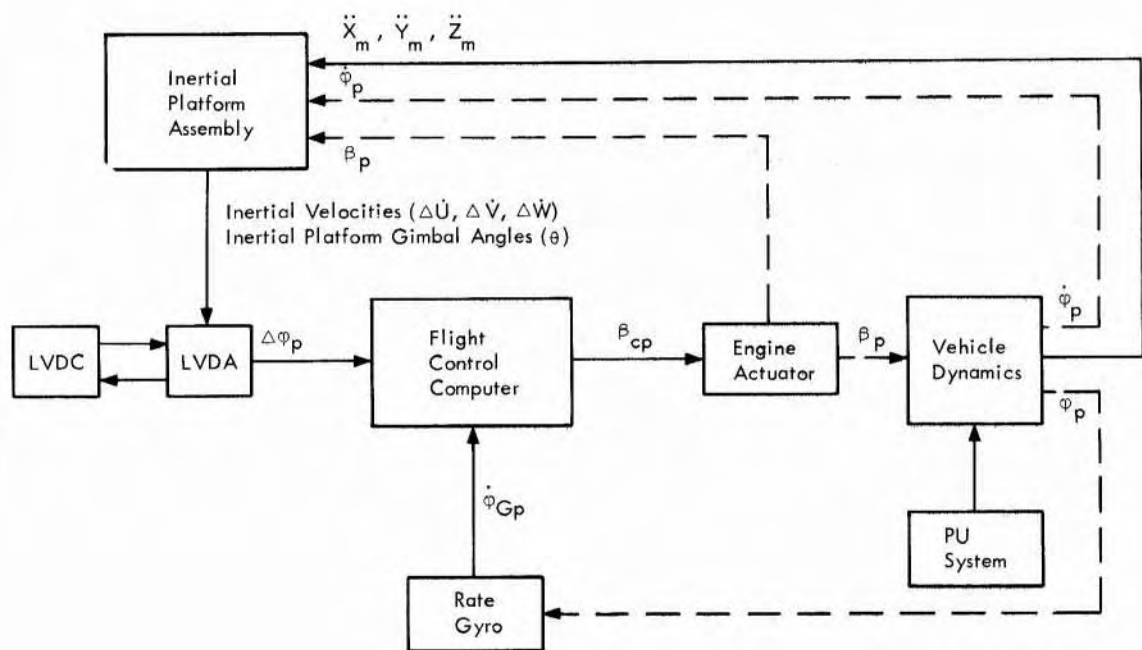
## Guidance and Control Loop

- $\chi$  = Commanded Gimbal Angles
- $\theta$  = Actual Gimbal Angles
- $\psi$  = Attitude Error Signal in Inertial Frame
- $\Delta\phi$  = Attitude Error Signal in Vehicle Frame
- $\beta_c$  = Commanded Engine Angle
- $\beta$  = Actual Engine Angle



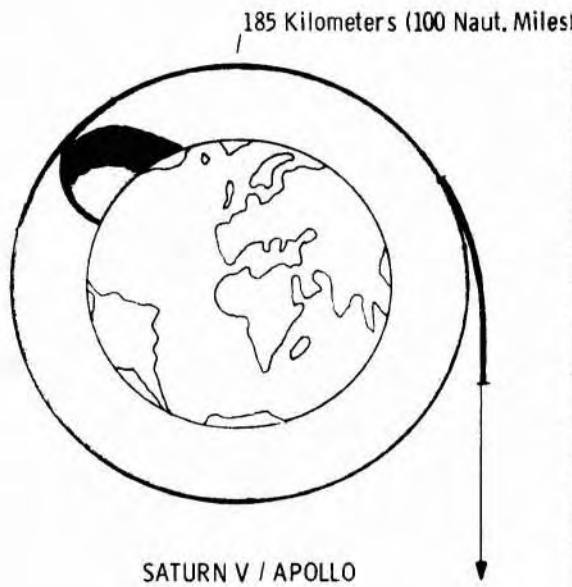
Slide 5

## Guidance and Control System



Slide 6

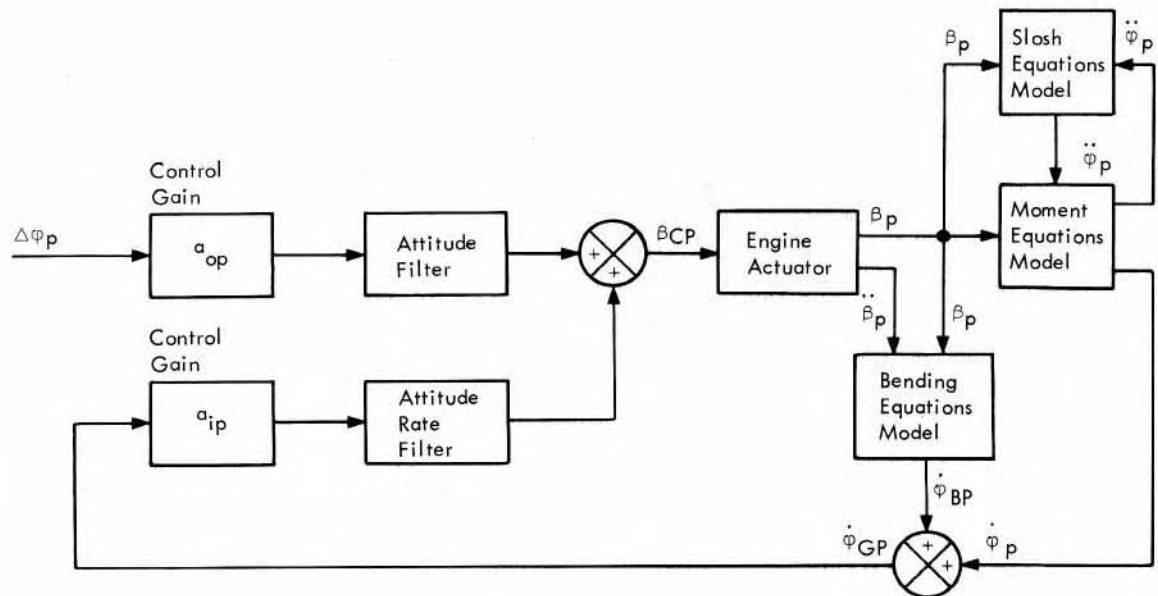
### FLIGHT COMPUTER TASKS BY PHASE



PHASE				TASK
1	2	3	4	5
PRIOR TO LIFTOFF				PRELAUNCH
x		x	x	x
		x	x	
x		x	x	x
x		x	x	x
x		x	x	x
		x		
		x		

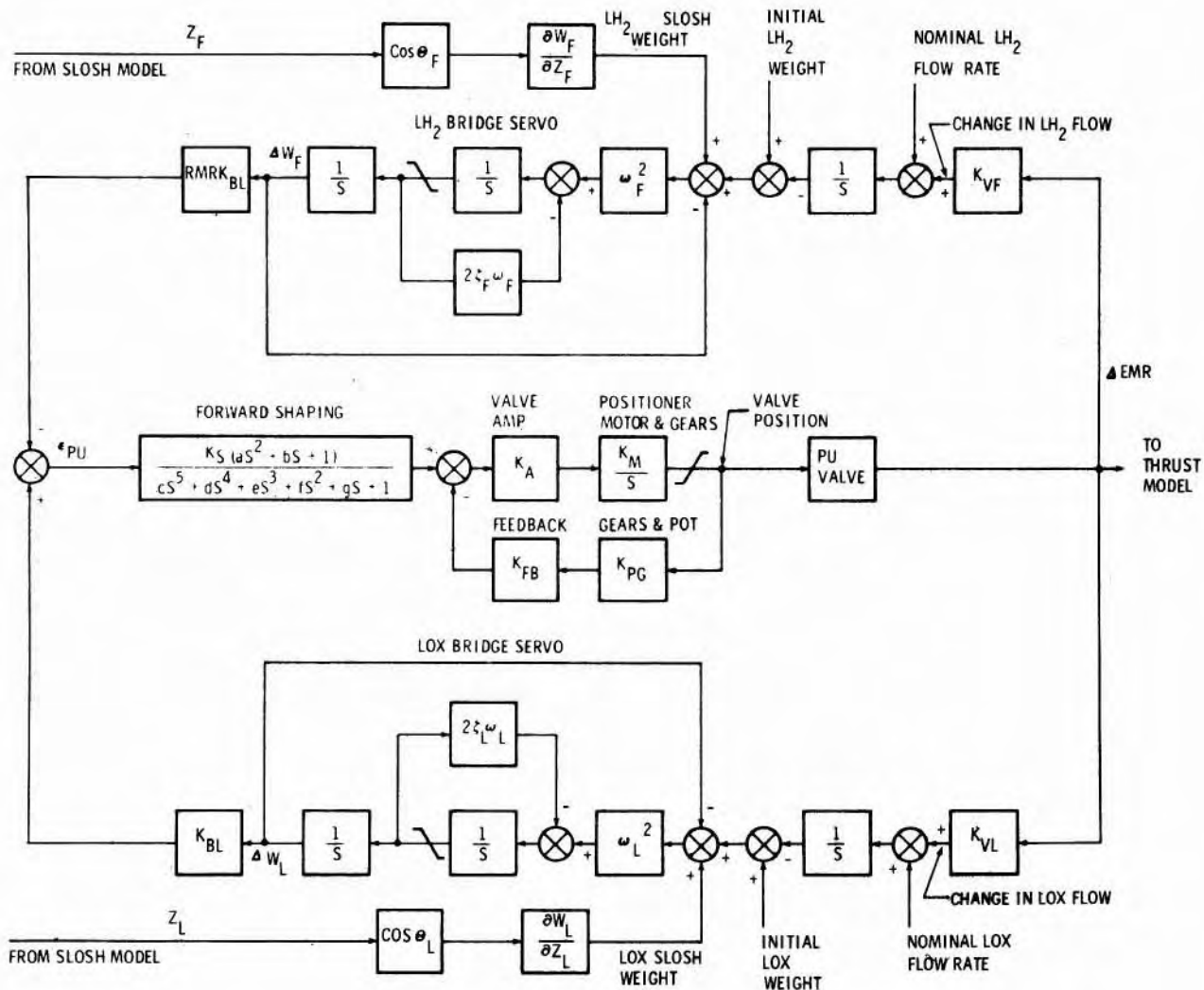
Slide 7

## Control Loop



Slide 8

# Propellant Utilization System



Slide 9

## ***Factors Related to Computing Task Assignments in Hybrid Simulation***

### **1. APPLICATION**

- a. FREQUENCY CONTENT
- b. PRECISION REQUIREMENTS
- c. SYSTEM COMPOSITION
- d. FLIGHT EQUIPMENT INTERFACE
- e. TYPE OF SYSTEM

### **2. COMPUTER HARDWARE**

- a. MEMORY SIZE AND SPEED OF DIGITAL MEMBER
  - b. EQUIPMENT CONFIGURATION OF ANALOG MEMBER
  - c. LINKAGE CHARACTERISTICS
  - d. COMMUNICATION CHANNEL COUNT AND PRECISION
- VS
- CONSOLIDATION OF SMALL COMPUTING TASK ON ONE MACHINE



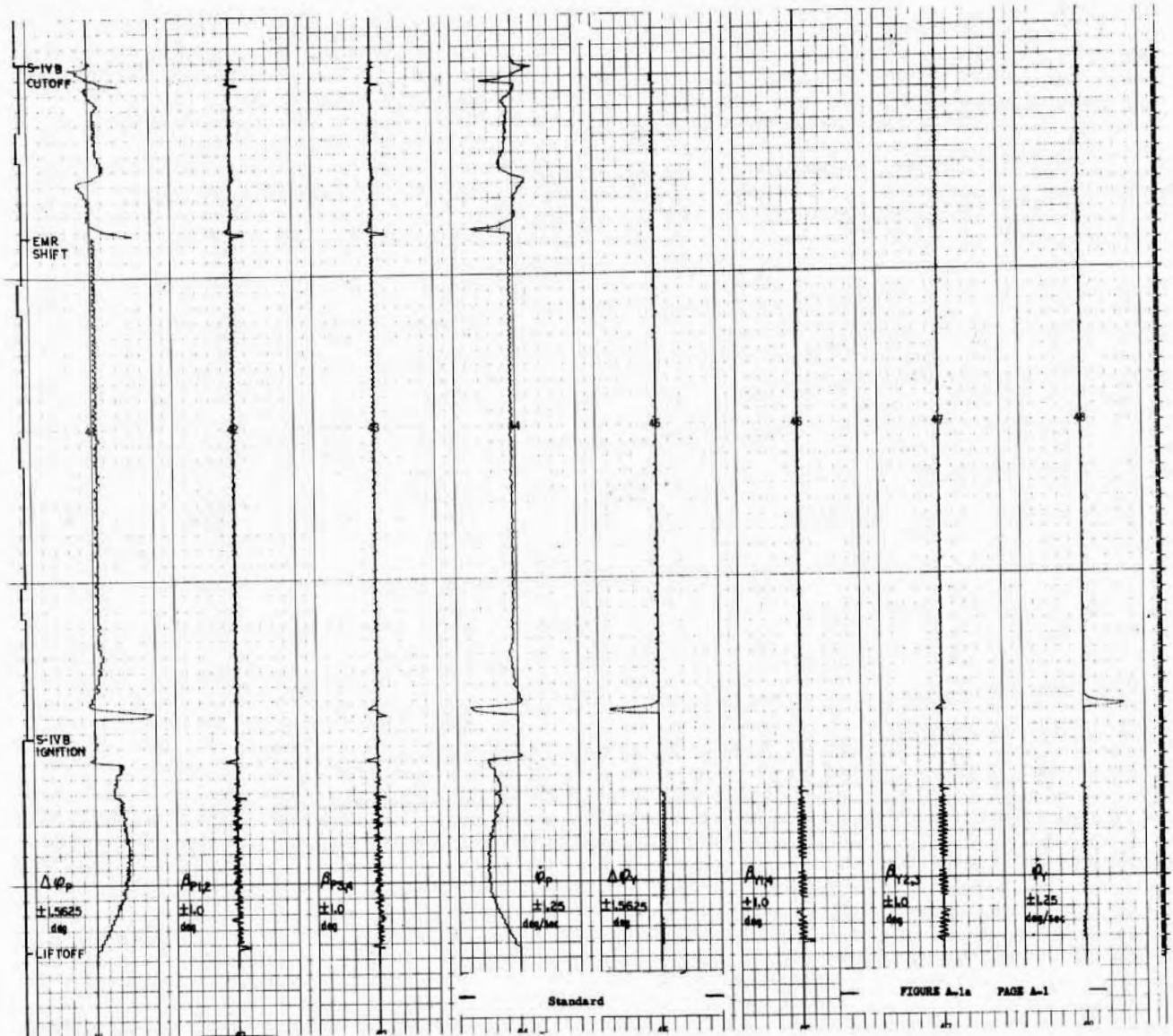
# ***Computing Task Assignment***

## **ANALOG**

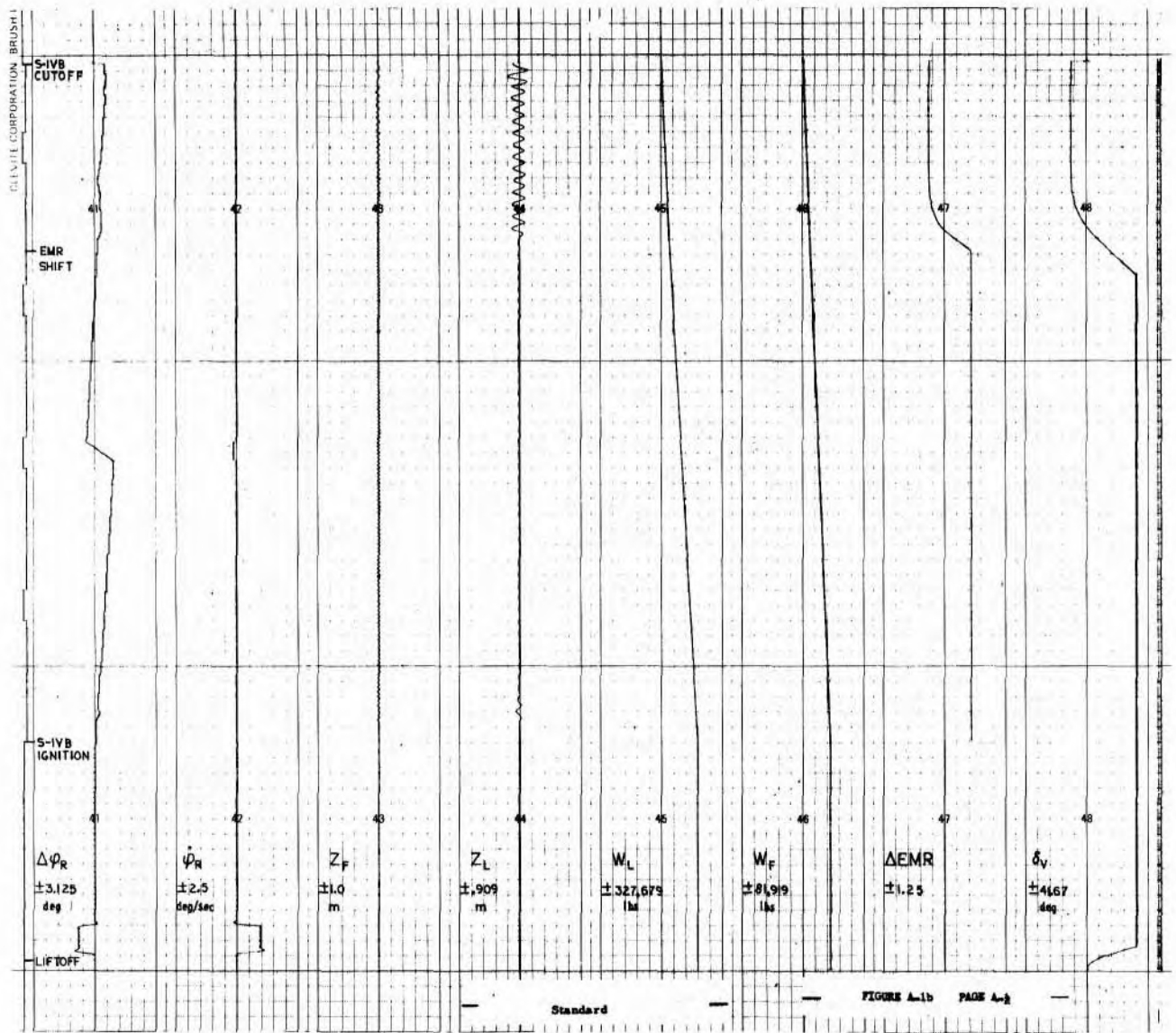
- FLIGHT CONTROL COMPUTER
- CONTROL ACTUATOR
- MOMENT EQUATIONS
- PROPELLANT SLOSH MODEL
- BODY BENDING MODEL
- PROPELLANT UTILIZATION CONTROL SYSTEM

## **DIGITAL**

- INERTIAL PLATFORM
- TIME AND/OR MASS VARYING FUNCTIONS GENERATION
- NAVIGATION MODEL
- TELEMETRY GROUND STATION
- CONTROL OF AUTOMATED SET-UP AND CHECKOUT OF ANALOG
- PROPELLANT UTILIZATION SYSTEM VALVE AND PUMP MODELS
- DATA REDUCTION AND PREPARATION



Slide 12



Slide 13

