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**EARTH ORBITAL TELEOPERATOR
MOBILITY SYSTEM EVALUATION PROGRAM**

TEST REPORT NO. 1

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EARTH ORBITAL TELEOPERATOR
MOBILITY SYSTEM EVALUATION PROGRAM

TEST REPORT NUMBER 1

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FOREWORD

This 1976 year end Mobility Laboratory Report is one of a set of three volumes that describe the teleoperator design studies performed by Essex Corporation under NASA contract NAS8-31848. The three volumes describe the tests conducted in the mobility, manipulator and visual laboratories at Marshall Space Flight Center (MSFC) and the concomitant results. This effort was directed by Mr. Edward G. Guerin (COR).

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1.0 EXECUTIVE SUMMARY

The National Aeronautics and Space Administration (NASA) is currently considering remotely controlled teleoperator systems for a number of space missions including payload applications, mass handling, and structure assembly. The George C. Marshall Space Flight Center (MSFC) has the responsibility for development of three primary teleoperator technology areas including:

- Visual Systems
- Manipulator Systems
- Mobility Systems.

This report describes a simulation study of vehicle maneuvering and docking with a target satellite. A critical performance requirement for a teleoperator vehicle will be remote control of vehicle mobility to permit approach to and docking with objects in orbit. To permit testing of hardware and procedural aspects of mobility and docking, tests were run using air-bearing technology to provide a five degree-of-freedom simulation of a cold gas propelled teleoperator vehicle and target satellite.

The mobility and docking laboratory used for the tests contains a precision epoxy test surface, a free flying mobility unit containing air bearing, pneumatic thruster, and control subsystems, a target satellite, and a remote control station with suitable telemetry links.

The objective of the tests performed to date was to obtain baseline data on system performance in near proximity maneuvering and final docking under various thruster conditions, target initial positions, target mass levels, and thruster control modes. A secondary objective was to develop and refine

the MSFC capability to investigate proposed teleoperator system components including the video system, docking mechanisms and control system concepts.

In the current test effort, the operator used the remote video and controls to command thruster firings and reduce the vehicle-to-target range. During approach, the operator monitored aim point and range rate as necessary to complete the final approach and achieve a hard dock with the target. The independent variables included:

- Target mass level
 - 1) Large (air bearing system off - no induced target motion, no thruster impingement effects)
 - 2) Small (air bearing system on - improper vehicle contact and/or thruster impingement will cause target motion).
- Thrust mode
 - 1) Continuous thrust when controller is out of detent
 - 2) Pulsed thrust at 5.5 pulses per second when controller is out of detent.
- Initial position
 - 1) Teleoperator camera LOS boresighted with target longitudinal axis
 - 2) Teleoperator camera LOS offset $\pm 45^\circ$ with respect to target longitudinal axis.

The dependent measures used were elapsed time from run initiation to hard dock and propellant consumption.

Analysis of variance performed using the time raw data did not result in significant effects of any of the independent variables. The general mean time over all conditions was 4.1 minutes.

Analysis of fuel consumption showed a significant main effect of thrust mode and a significant three-way interaction. The thrust mode main effect was found to consist of a 30% reduction in propellant consumption using the

pulse mode when compared with the constant thrust mode.

The three-way interaction between the independent variables was due to the fact that the thrust mode effect was particularly pronounced for the floating satellite at 0° offset.

2.0 INTRODUCTION

The National Aeronautics and Space Administration is currently considering remotely controlled teleoperator systems for a wide range of space missions including payload applications, large space structure assembly, hazardous environment applications and space environment experimentation. Partial responsibility for the development of free flying teleoperator technology has been assigned to NASA's George C. Marshall Space Flight Center which has been conducting a research program for teleoperators for the past six years. This report deals with human operator investigations conducted by Essex researchers at the Marshall Space Flight Center.

Teleoperators are remotely controlled man-machine systems which serve to augment and extend the human's sensory and manipulative capabilities into hostile or distant environments. As currently conceived, teleoperators will be equipped with visual sensors and feedback systems, dexterous manipulator systems and control systems for maneuvering and mobility. The operation of these systems will be under the control of a human operator at a remote site.

NASA's MSFC is currently developing teleoperator technology to support the design, development and on-orbit testing of the Space Teleoperator Evaluation Vehicle (STEV). In a typical teleoperator evaluation mission, the STEV will fly aboard the Shuttle transportation system and be deployed to perform satellite servicing tasks on an experimental basis. The work performed by Essex researchers is in direct support of the development of design criteria and selection of teleoperator system components for this Shuttle payload.

The space teleoperator mission may take the form of repair, refurbishment,

data retrieval, insertion or extraction from orbit of a satellite or some similar servicing function, with the teleoperator under remote control of a human operator who is located either in the Space Shuttle or at a ground station. The teleoperator, with its propulsion, sensor, docking and manipulator systems, would be deployed from the Shuttle, move to the vicinity of the target satellite, make a final approach and dock with or grapple the satellite. The teleoperator will then perform the scheduled servicing of the satellite or return the captured satellite to the Shuttle for onboard servicing or stowage for return to earth.

The current report describes a simulation study of the proximity translation and final docking of the STEV with large mass and small mass* satellites. These tasks approximate operations that may be performed by the STEV during the Shuttle experiments.

* The small mass class target is considered a passive docking receptor (i.e., free floating) and is sometimes referred to as a "passive satellite" in this report.

3.0 FREE FLYING TELEOPERATOR DOCKING SIMULATOR DESCRIPTION

The free flying mobility unit was designed to investigate the guidance and control problems associated with a small, unmanned, remotely controlled space vehicle in a near proximity rendezvous and docking situation. For the purposes of this testing program, the mobility unit has two degrees-of-freedom in translation (fore/aft and left/right) and one degree-of-freedom in attitude (yaw). All vehicle maneuvers are achieved by appropriate commands to 16 pneumatic thrusters acting either symmetrically for translation or asymmetrically for vehicle attitude changes. The arrangement of the thrusters on the vehicle are such that all control forces surround the vehicle's center of gravity with all rotational torques applied as nearly pure control couples.

The target satellite top bay is painted non-glare white and the air bearing base is painted flat black which, when viewed against a black background, provides a realistic space background image on the operator's monitor.

The main subsystems which comprise the laboratory teleoperator are:

- 1) command subsystem
- 2) video subsystem
- 3) telemetry subsystem
- 4) control and fuel subsystem.

Several potential payloads may require servicing and/or retrieval by the teleoperator. The range of satellite volume and mass in this group is varied, extending from those which are smaller to those much larger than the teleoperator. Therefore, the mass-class of the target satellite has a direct effect on the docking position of any mission since thruster impingement by the teleoperator during docking could alter the position and attitude of the target, thereby increasing fuel consumption and elapsed time required to dock. For the purpose

of this study, the target satellite was of equal volume to the teleoperator (low mass class). However, since the satellite has the capability to free-float on special air bearing pads for the low mass case, it was decided to use this same satellite vehicle to simulate large mass class targets by turning off the air supply to these pads and fix the docking target in position and attitude. A small mass class satellite could be simulated by activating the air pads to make the satellite capable of responding to teleoperator thruster impingement and contact by the teleoperator during docking attempts. During the test runs, fuel consumption, time to dock and the number of docking aborts were recorded.

3.1 COMMAND SUBSYSTEM

The command subsystem, shown schematically in Figure 3-1, has nine sub-carrier frequencies operating on nine 450 MHz range carrier frequencies which have the capability to be excited two at a time. This yields a potential of 36 command signals. The command signals are generated at the operator's console via a single three degree-of-freedom hand controller. The hand controller, when displaced, closes a set of relays which transmits binary signals to the mobility unit. These signals activate appropriate solenoids to modify the teleoperator position or attitude by thruster firings.

Thruster firing signals are of two types: (1) a constant mode in which the telemetered signal is transmitted for the duration of the command which results in a constant "ON," or (2) a trained mode in which the telemetered signal is pulsed at 5.5 bursts per second and transmitted at this rate for the duration of the command.

3.2 VIDEO SUBSYSTEM

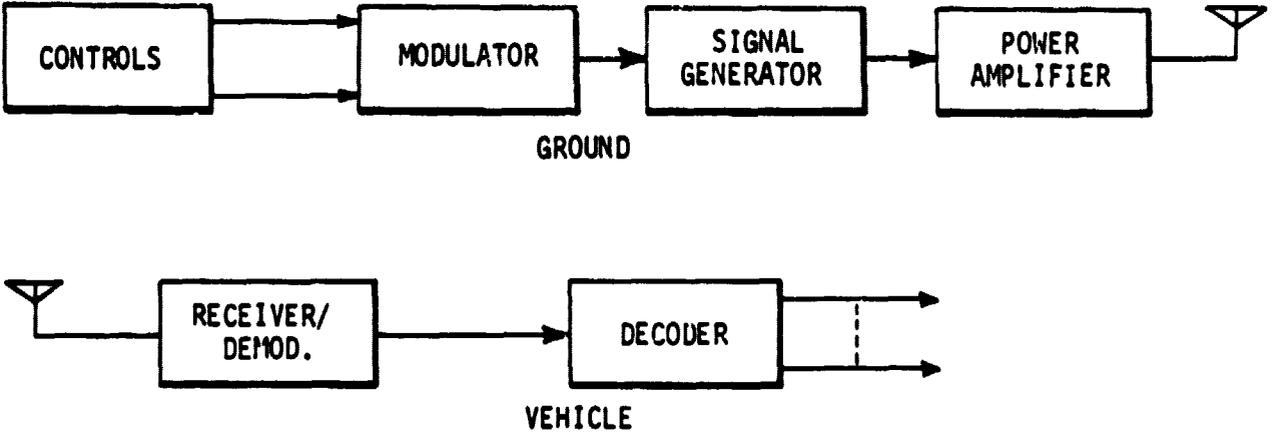


Figure 3-1: Command Subsystem

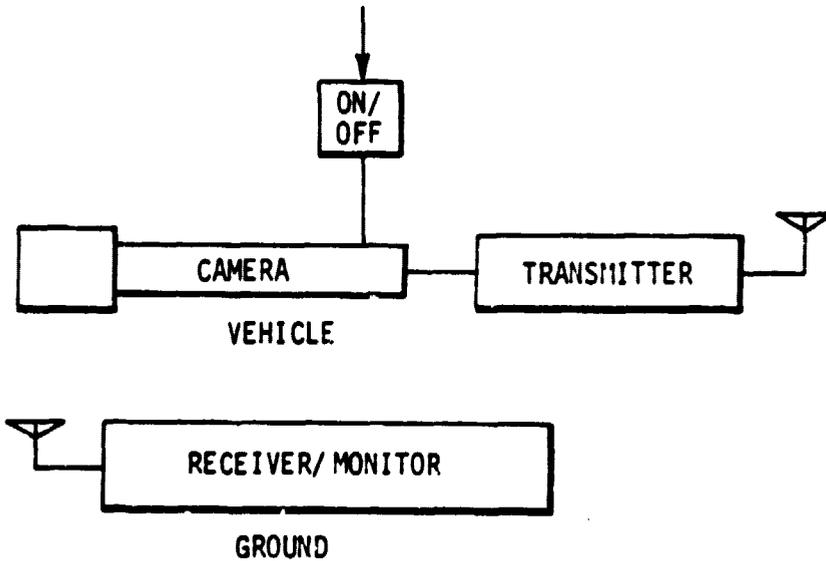


Figure 3-2: Video Subsystem

3.2.1 Camera

The teleoperator video subsystem utilizes a single onboard camera which is boresighted with the longitudinal axis of the mobility unit and mounted directly above the docking probe. The video subsystem is schematically presented in Figure 3-2. The camera is a COHU Model 2840 which is a low light level model modified to operate on 28 vdc. The camera lens is a Canon model TV-16, 25 mm, 1:1.4 which uses an automatic iris control. Zoom and focus, however, were preset for the testing program.

3.2.2 TV Monitor

The video signal was telemetered via channel 9 (VHF) to a Sony Corporation, Model PVJ-51Rü, 22.9 cm (9 in.) commercial black and white monitor located at the operator's console.

3.3 TELEMETRY SUBSYSTEM

The telemetry subsystem is shown in Figure 3-3. This system operates in the 253 MHz range and has the capability of 17 channels for data transceiving. However, for this program, only three channels were monitored for feedback of the following data:

- battery voltage
- onboard fuel remaining
- docking status.

3.4 CONTROL AND PROPULSION SYSTEMS

This system is schematically presented in Figure 3-4. The control system is operated in the open-loop or supervisory mode, where the operator determines the vehicle's orientation and velocity via video feedback and makes all position and attitude corrections by firing the selected thrusters.

During the tests, only three axes were controlled - fore/aft and left/right in translation, and yaw in attitude. The mobility vehicle's propulsion

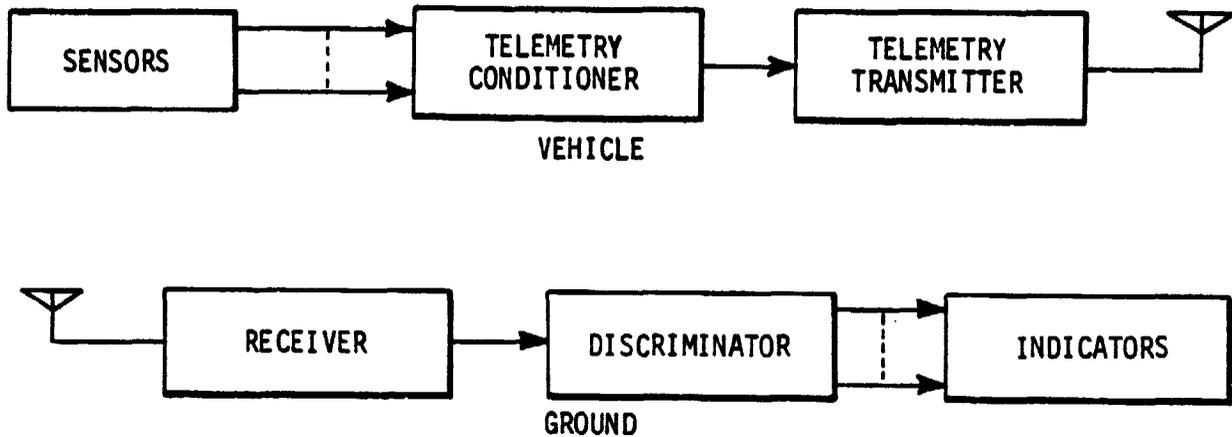


Figure 3-3: Telemetry Subsystem

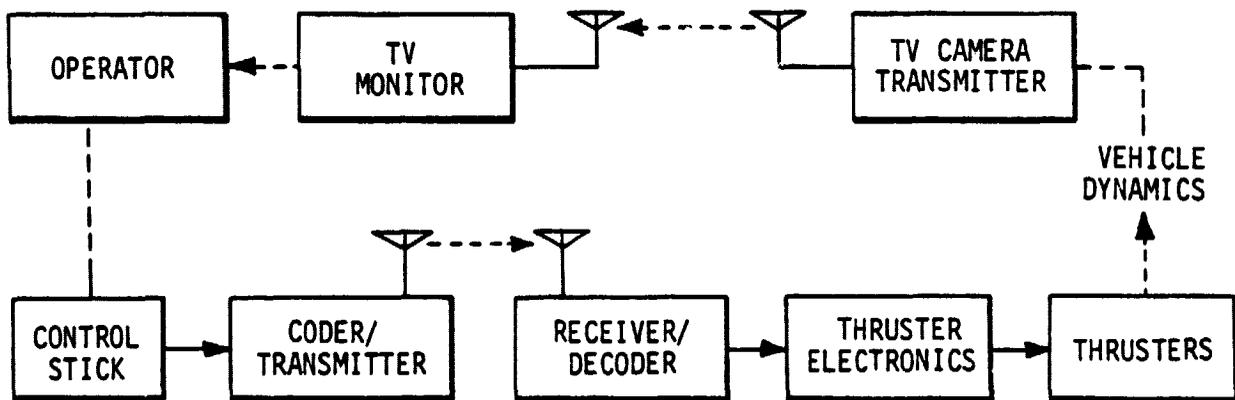


Figure 3-4: Open Loop Control System

system uses compressed air which was operated through four groups of four thrusters each that provide pure moment and axial thrust. The propulsion system is graphically presented in Figure 3-5 and the command thruster logic is presented in Table 3-1.

The air bearing system consists of three 30.5 cm (12 in.) circular air pads, pressure regulated at $2.4 \times 10^5 \text{ N/m}^2$ (35 psi) to float the vehicle with a .02 mm (.001 in.) clearance. The total volume of compressed air stored in the lower bay of the vehicle is $.074 \text{ m}^3$ (2.604 ft^3) at a pressure of 10.3 N/m^3 (1500 psi). The lower bay, in addition to housing the compressed air supply and containing the air pads, also serves as a mounting support for a pedestal to which the upper bay is mounted. This lower bay is 48.3 cm high and 116.8 cm in diameter (19 in. by 46 in.) and is painted a non-reflective flat black to minimize the operator's visual cues.

Table 3-1: Thruster Command Logic

Thruster Command	Thruster Response
Foreward	14, 15
Aft	6, 7
Right	8, 16
Left	5, 13
Yaw Left	5, 16
Yaw Right	8, 13

The propulsion system of the teleoperator vehicle, as mentioned earlier, serves the dual purpose of vehicle translation and attitude control. Each group of four thrusters is clustered about the longitudinal axis of the vehicle (one group at each corner). Each thruster is controlled by a solenoid valve at the thrust chamber injector and is bench calibrated at 4.45 n (1 lb.) thrust

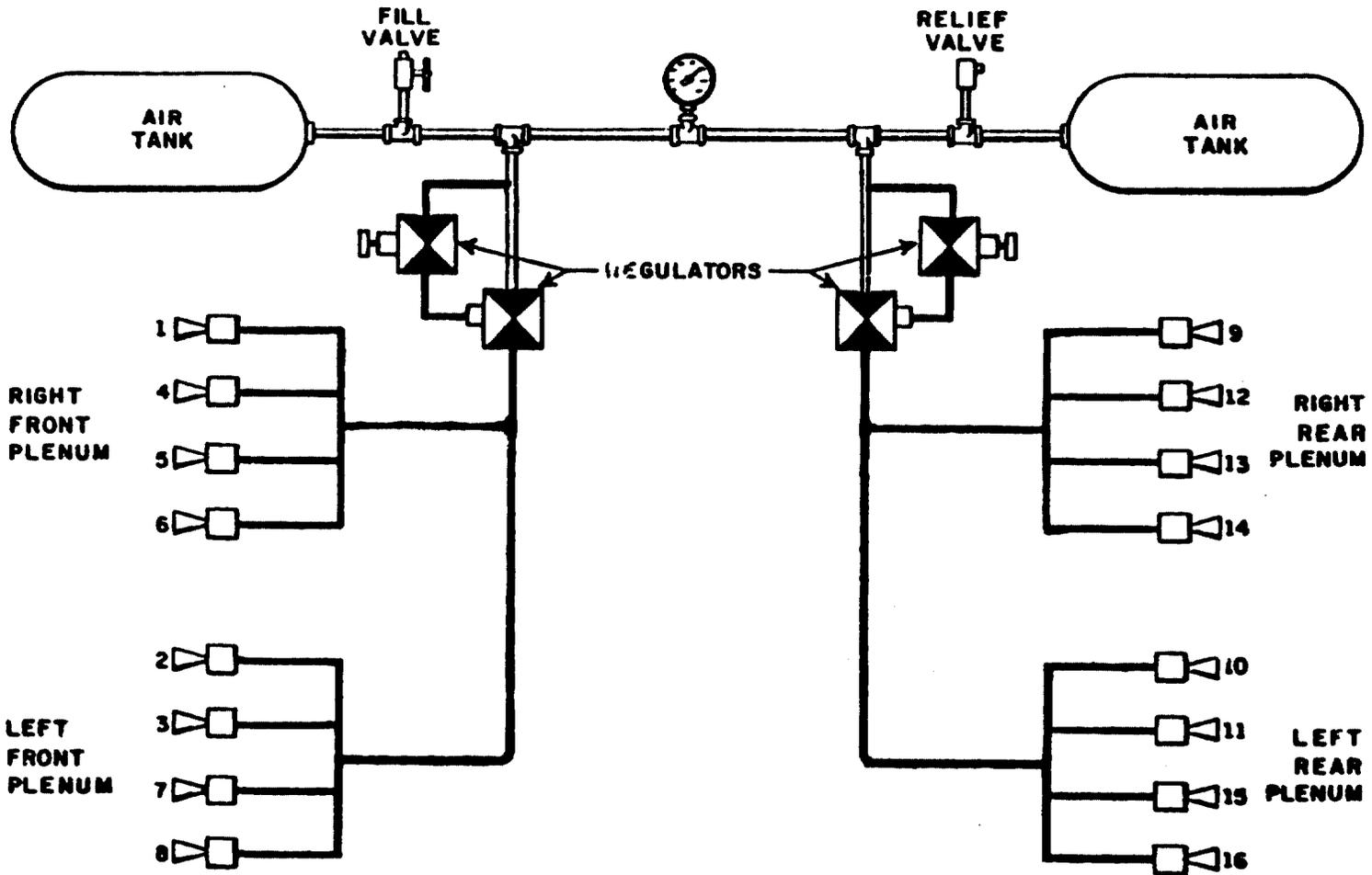


Figure 3-5: Compressed Air System

for 4.12×10^5 n/m² (60 psi) plenum pressure and a 100 msec pulse duration. Total volume of compressed air for the upper bay of the vehicle is 0.074 m³ (2.6 ft³) at a rated pressure of 10.3 n/m³ (1500 psi).

Total weight of the vehicle is approximately 445 kg (1000 lbs.) of which 325 kg (730 lbs.) is the top bay.

3.5 LABORATORY DESCRIPTION

The facility consists of a high precision test surface with the dimensions shown in Figures 3-6 and 3-7. This was enclosed within a 12.2 by 12.2 by 6.1 m (40 by 40 by 20 ft) black curtained room. The area is air conditioned to maintain a relatively constant temperature for the precision floor and to minimize the accumulation of debris on the surface of the floor and vehicles.

The test surface is a poured, black 2.54 cm (1 in.) thick, hard, epoxy type REN DC 84-66 which has less than a 0.01 cm variation as measured over 125 separate locations.

Illumination of the test area is by four 1000 watt quartz iodine lamps (two in each corner) suspended from the ceiling at one end and angled to converge the greatest illumination near the center of the test area where the satellite is positioned. Angling of the light enhances the simulation effect of a space mission and reduces the number of visual cues (shadows) which the operator could use for final alignment and docking.

Adjacent to the test area is the operator's test console which is enclosed in a 9.0 m² (95 ft²) sound insulated room. The test console provides a resemblance to the Shuttle aft cabin control station. The present simulation was concerned with only a portion of the entire teleoperator mission. Therefore, it was unnecessary to include all controls and displays of the entire proposed STEV mission.

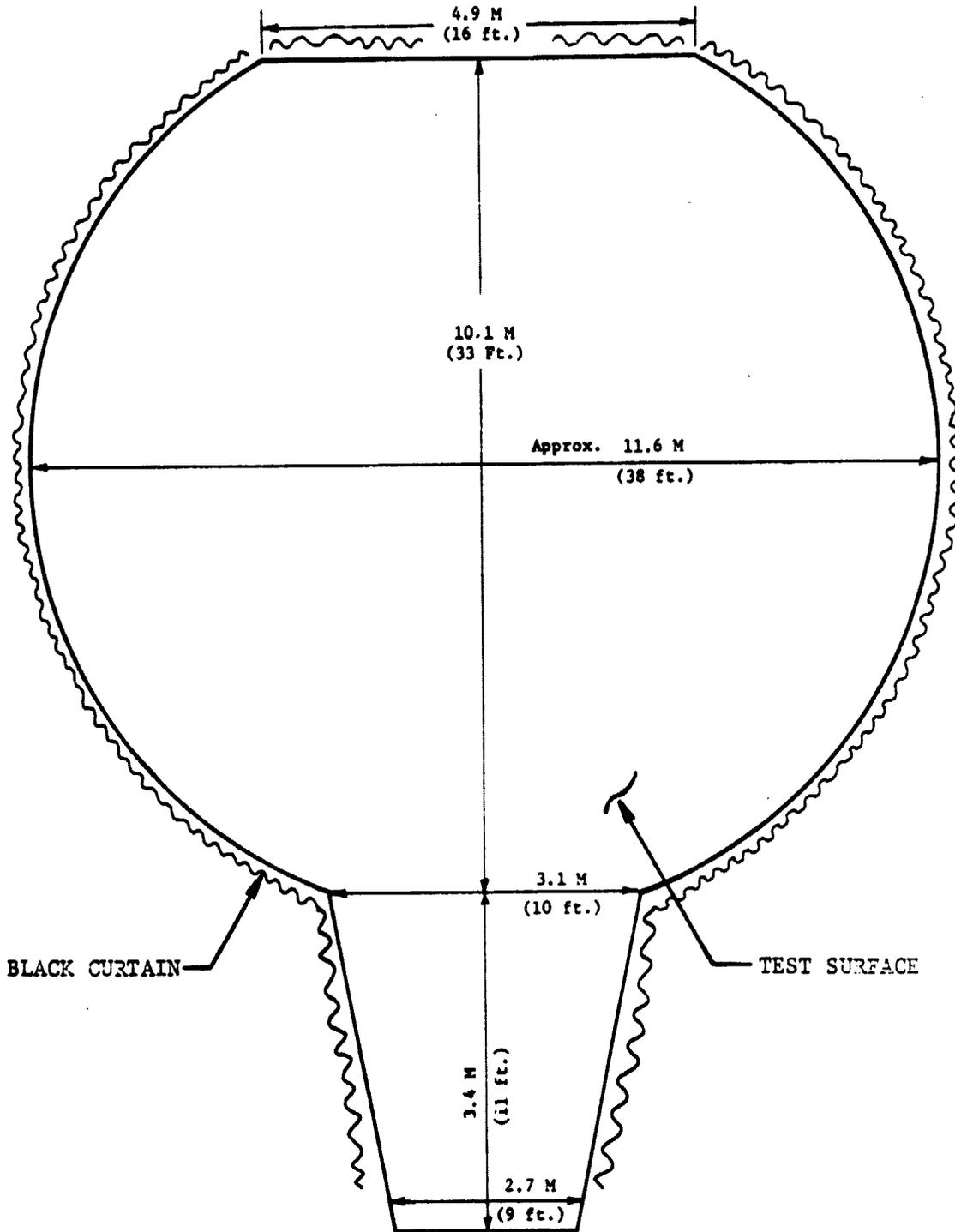


Figure 3-6: Docking Simulator Test Surface

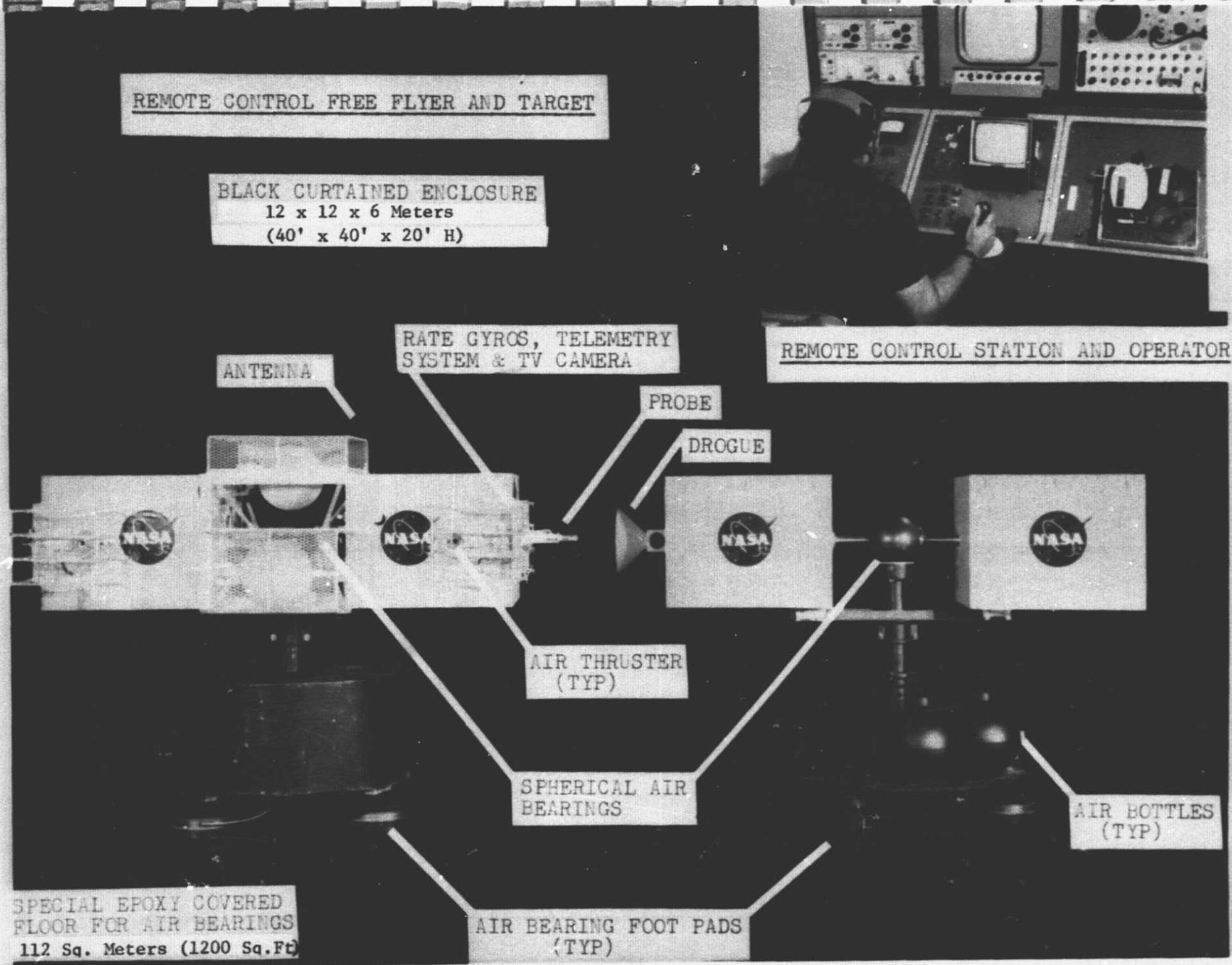


Figure 3-7: Free Flyer Mobility Unit and Target Satellite

The control station (as shown in the upper right-hand corner of Figure 3-7) contains a TV monitor displaying the satellite image which was the only display the subject used. In addition to the TV monitor, the console had a single, spring-loaded, center return, three degree-of-freedom hand controller (capability of the controller was 5 DOF). By displacing the controller in the desired direction, the hand controller provided a direct physical correspondence to the teleoperator direction of movement. A single lamp to the right of the controller was illuminated when the docking probe had penetrated the docking drogue approximately 16 cm (6 in.) and was centered within the throat. This lamp signaled the completion of a trial and also terminated the elapsed time indicator.

The free flying mobility unit and target satellite are presented in this section since they are part of the laboratory's integrated systems. The free flying mobility unit is shown in Figure 3-8, and the target satellite is shown in Figure 3-9. The physical dimensions of both systems are nearly identical with respect to the upper bay as seen in Figure 3-7. Therefore, the dimensions shown are applicable for both systems.

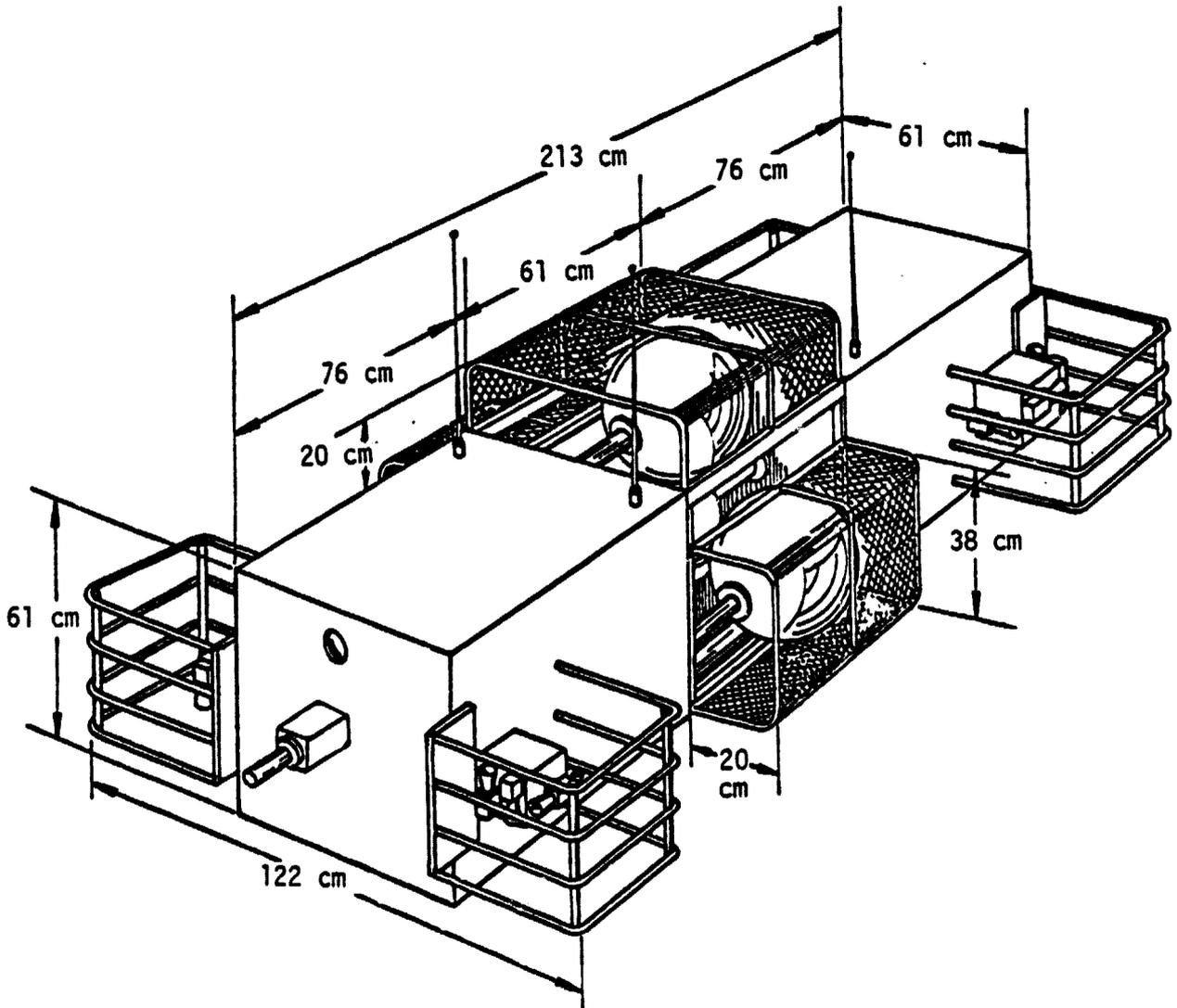


Figure 3-8: Teleoperator Mobility Unit

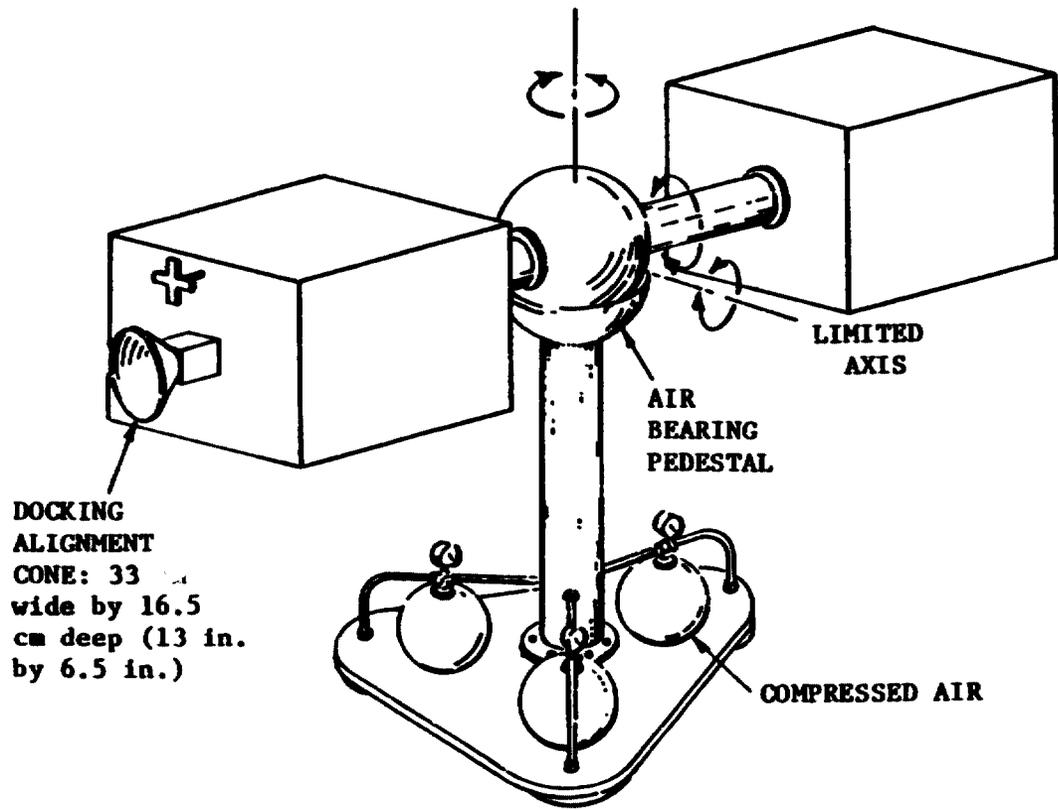


Figure 3-9: Docking Satellite Configuration

4.0 TEST OBJECTIVES, PROCEDURES AND EXPERIMENTAL DESIGN

4.1 TEST OBJECTIVES

The primary objective of this series of tests was to gather baseline operator performance data on near proximity maneuvering and final docking of the free flying teleoperator with a target satellite under various conditions of target initial position, target mass class (large and small mass), and teleoperator thruster modes.

The secondary objective was to develop and refine the MSFC capability to investigate proposed teleoperator system components such as the video system, docking aids, hand controller and control laws.

4.2 TEST PROCEDURES AND APPROACH

The simulation approach involved the air bearing free floating technique described in Section 3.0 of this report. The test method employed for this study dictated that half of the trials be conducted with the target satellite in a fixed position on the air bearing floor to simulate a large mass class target. The other half were conducted with the target passive or free floating in position and attitude to simulate a small mass class satellite that would be disturbed by the teleoperator thruster impingement.

The general procedure for each trial consisted of the operator commanding the mobility unit to close range on the target which was located in the center of the floor. The operator made continual alignments of the mobility unit's position and attitude to fly the probe into the target's drogue. When a hard dock was successful, a docking latch lamp illuminated on the operator's panel. If a docking was aborted as indicated by increasing the range, a docking trajectory was re-established and another docking attempt was made. At the

completion of each docking, the dependent data were recorded, the mobility unit was repositioned, and a new trial was begun. See Figure 4-1.

4.3 EXPERIMENTAL DESIGN

The independent variables include:

- Target satellite mass class
 - 1) Large (stable, attitude-locked, no air bearing pads)
 - 2) Small (passive, attitude-locked, using air bearing pads)
- Teleoperator thrust mode
 - 1) Constant ("bang-bang")
 - 2) Trained (5.5 pulses per second)
- Teleoperator/target initial position displacement
 - 1) LOS (boresighted with satellite longitudinal axis)
 - 2) Offset (+45° NW or NE with respect to the satellite longitudinal axis)

Each variable was manipulated at two levels requiring 12 trials per subject. The order of trial presentation was randomized over all subjects to the extent possible by blocking of system parameters (e.g. floating satellite or fixed satellite).

The variables that were controlled during each test run were:

- Test area lighting - two banks of two 1000 watt quartz iodine lamps
- Initial propellant pressure - $10.3 \times 10^6 \text{ n/m}^2$ (1500 psi)
- Battery voltage - 28 vdc
- Initial range (teleoperator CG to satellite CG) - approximately 7.5 m (25 ft)
- Operator's TV monitor - daily check for high quality picture
- Initial position of target satellite - approximate center of floor
- Test surface - daily cleaning
- Subjects - five subjects completing 12 trials each.

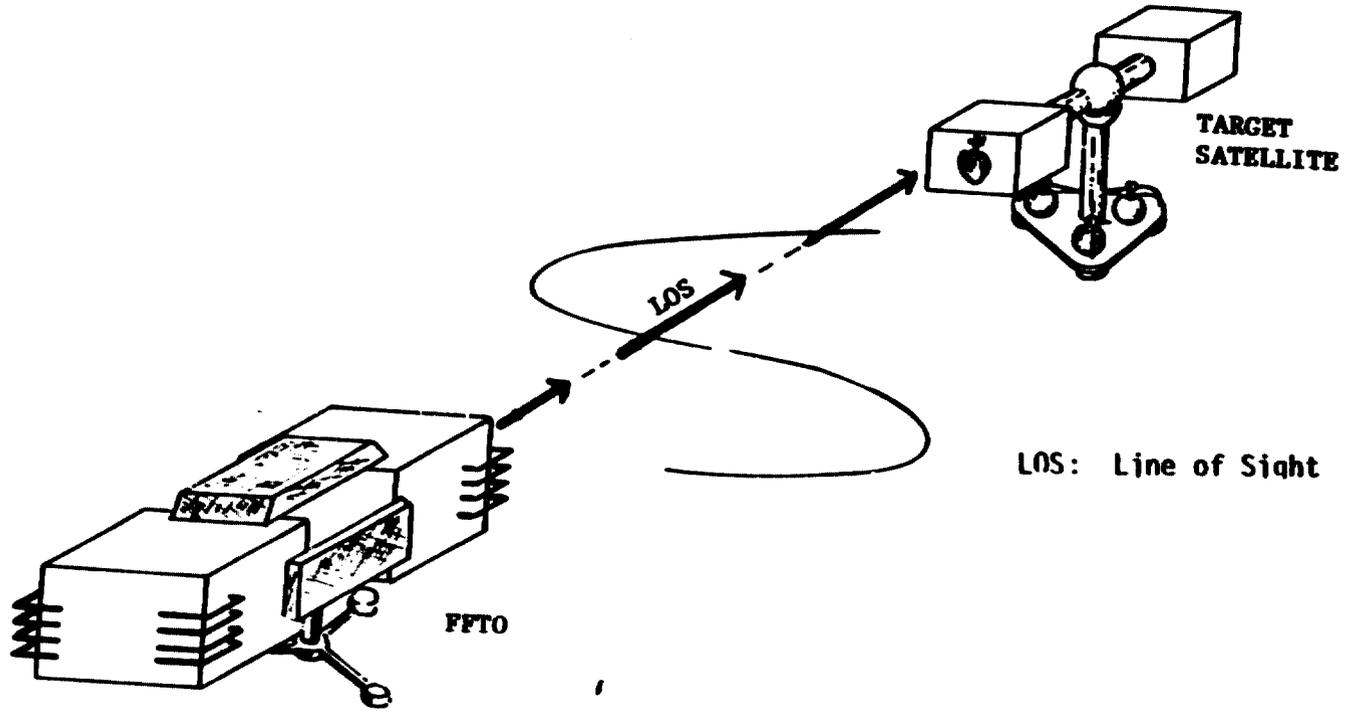


Figure 4-1: Docking Simulation Concept

The dependent measures recorded during each test were:

- Elapsed time for docking
- Fuel consumed for docking

4.3.1 Elapsed Time for Docking

The time required for docking is an obvious figure of merit for system/operator performance. Presumably the longer the time required, the greater the difficulty of the tasks associated with a particular test condition. In addition, studying completion time as a function of the independent variables employed permits detection of differential effects of these variables on different tasks. For example, attitude control system effects would be expected during the final approach to a greater degree than during initial translation. Furthermore, completion time data will be required for time-line STEV mission planning and workload analysis. If task completion were time constrained during a mission, such data could be used to analyze the probability of task completion in connection with reliability analyses.

4.3.2 Fuel Consumed for Docking

The considerations which were stated in connection with completion time also apply to fuel consumption. This measure serves as a performance figure of merit - particularly since errors in aligning the mobility unit and satellite body axes will require correction which will be reflected in increased fuel expenditure. Data on distributions of fuel required will also be useful in determining system design requirements.

5.0 RESULTS AND CONCLUSIONS

The raw data (time and fuel consumption) were subjected to a four way analysis of variance with all factors fixed except subjects. Each of the two dependent measures was analyzed individually. The resulting source tables are presented in Tables 5-1 and 5-2.

5.1 ELAPSED TIME FOR TRIAL COMPLETIONS

Analysis of mean elapsed time per trial revealed no significant relationships. Therefore, these data are presented for information purposes only. In general, the mean elapsed time across all conditions was 4.1 minutes with the greatest elapsed time generated with the mobility unit positioned at approximately 45° to the right (NE direction) of the satellite (4.5 minutes) and the least time (3.8 minutes) when positioned at 45° to the left (NW direction). When the satellite mass class (free floating vs. fixed) is examined for the main effect on elapsed time, the passive satellite shows nearly a 45 per cent increase in the time consumed (5.3 minutes versus 2.9 minutes) for docking.

5.2 FUEL CONSUMED DURING TRIAL

Analysis of the raw data for fuel consumption revealed significant main effects for thrust mode and significant interaction of starting position (or IC) by thrust mode by satellite mass class. Both reached a $P < .05$ level of significance, and these data are presented in Figures 5-1 and 5-2.

The main effect of thrust mode revealed that pulsed thruster firing used approximately 30% less fuel than the constant mode in which the thrusters were firing as long as the subject commanded.

Table 5-1: Analysis of Variance for Elapsed Time

<u>SOURCE</u>	<u>df</u>	<u>SUM OF SQUARES</u>	<u>MEAN SQUARE</u>	<u>F</u>
MEAN	1	3616138.0	3616138.0	14.20
INITIAL CONDITION (I)	2	19977.1	9988.5	.96
MASS (M)	1	312769.3	312769.3	6.95
THRUST (T)	1	16401.1	16401.1	.72
SUBJECTS (S)	4	1018723.0	254680.6	
IM	2	9770.5	4885.3	.44
IT	2	48994.2	24497.1	2.52
MT	1	2912.0	2912.0	1.03
IS	8	83448.3	10431.0	
MS	4	179888.6	44972.2	
TS	4	91396.3	22849.1	
IMT	2	109100.3	54550.2	3.80
IMS	8	89184.3	11148.0	
ITS	8	77740.3	9717.5	
MTS	4	11315.5	2828.9	
IMTS	8	114836.3	14354.5	

Table 5-2: Analysis of Variance for Fuel Consumption

<u>SOURCE</u>	<u>dF</u>	<u>SUM OF SQUARES</u>	<u>MEAN SQUARE</u>	<u>F</u>
MEAN	1	110935400	110935400	23.77
INITIAL CONDITION (I)	2	102936.3	51468.2	.72
MASS (M)	1	77040.3	77040.3	2.24
THRUST (T)	1	330033.3	330033.3	8.14*
SUBJECTS (S)	4	1867013.0	466753.3	
IM	2	56894.2	28447.1	.45
IT	2	148144.6	74072.3	2.02
MT	1	16666.1	16666.1	4.92
IS	8	574434.5	71804.3	
MS	4	137744.6	34436.2	
TS	4	162248.6	40562.2	
IMT	2	221264.6	110632.3	4.80*
IMS	8	509249.3	63656.2	
ITS	8	292993.3	36624.2	
MTS	4	13541.5	3385.4	
IMTS	8	184456.6	23057.1	

*P < .05

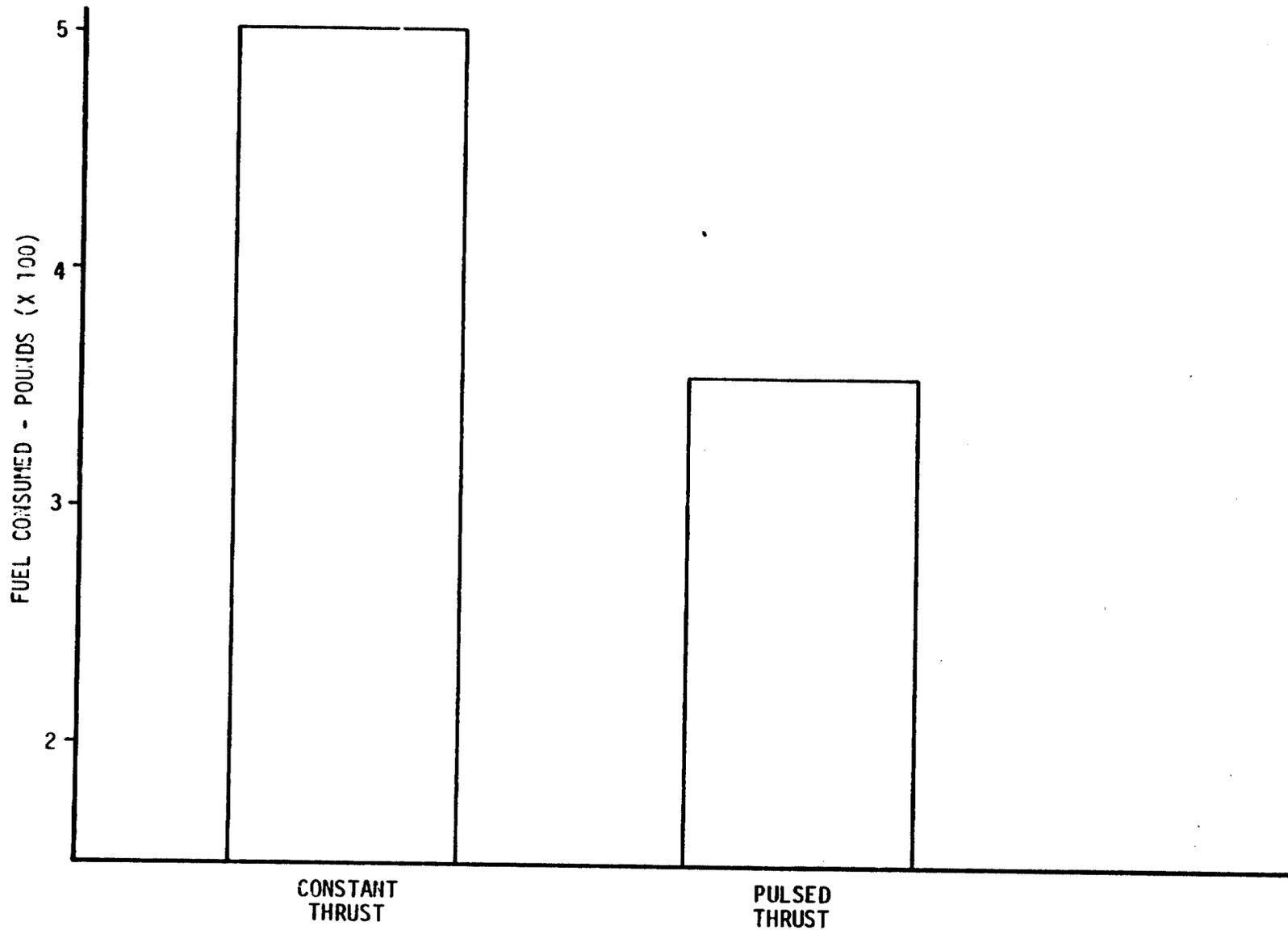


Figure 5-1: Fuel Consumed as a Function of Thrust Mode

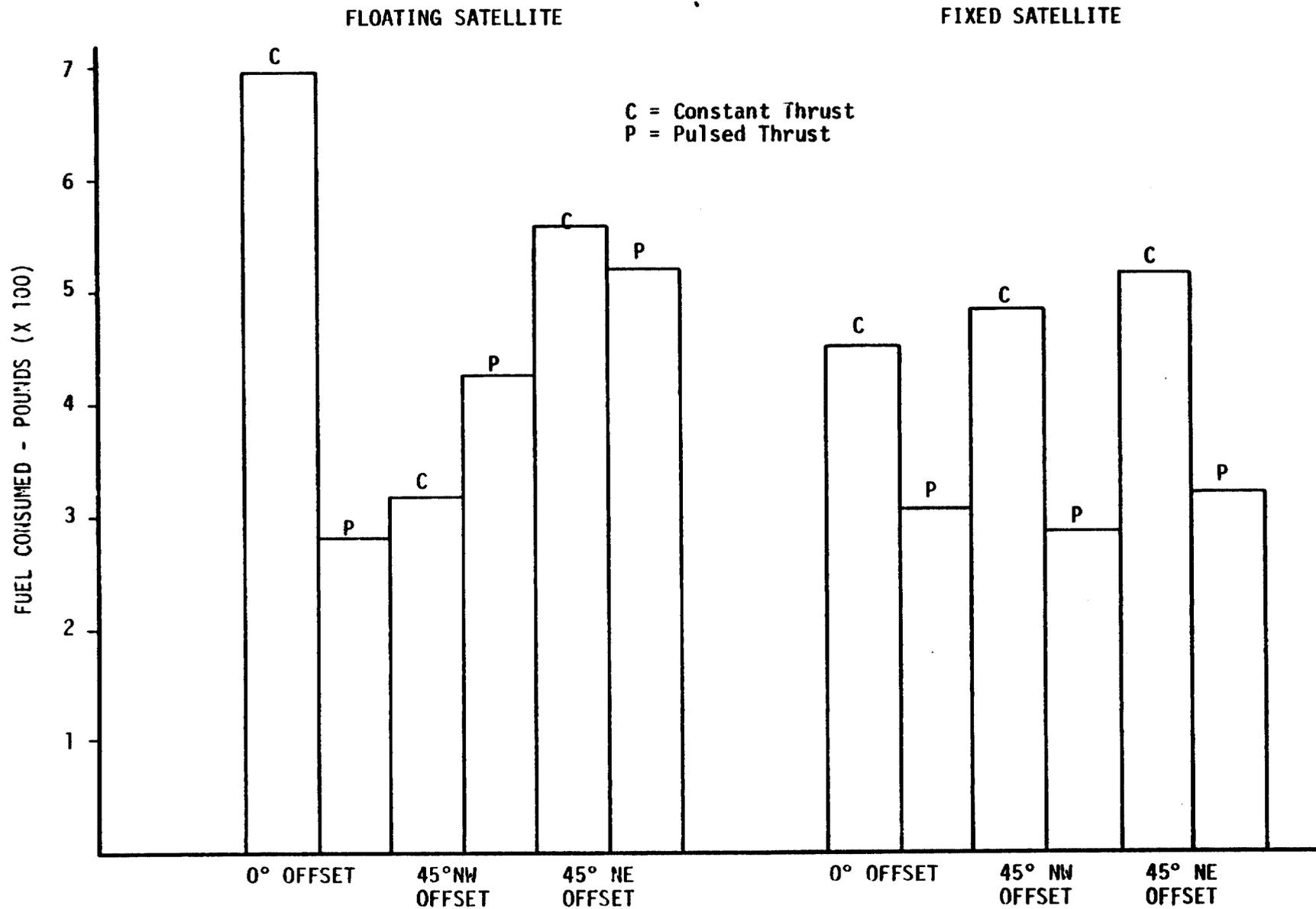


Figure 5-2: Fuel Consumed as a Function of Thrust Mode by Satellite Mass by Starting Position

Figure 5-2 presents mean fuel consumption as a function of the interaction of satellite mass class, by thrust mode, by starting position. As expected, mean fuel consumption was greater for a floating satellite than a fixed satellite. This appears to be due primarily to retro firings of the mobility unit on the satellite to either modify docking alignment or reduce the rate of closure. The fixed satellite generated a much tighter variance between conditions and illustrates the reduction in fuel consumption by using a pulsed thrust mode. A floating satellite starting condition with a zero degree offset and using a constant thrust mode revealed the mean fuel consumed was nearly half of the total on-board fuel whereas under the same satellite mobility unit conditions but using a pulsed thrust mode, the mean fuel consumption was the lowest value.

Based upon these data and with the conditions defined herein, it appears that a pulsed thrust mode will minimize fuel consumption while maximizing operating range and maneuvering capability of the STEV.

Future testing will define the problems associated with docking under conditions of a 5 DOF target satellite (fore/aft and left-right) in translation and pitch, roll and yaw in attitude) and will require a closed loop attitude control system that uses either reaction wheels or thruster firings. Concept evaluation will also be conducted to separate the functions of the existing single hand controller into two separate controllers since there exists a problem of inadvertent commands. Range and range rate aids for the operator need to be evaluated, either in the form of a static reticle or dedicated numerical displays, since relative position of the mobility unit with respect to satellite axes and residual closing rates were difficult for the operator to estimate.

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