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FINAL REPORT ON CONCEPTS AND REQUIREMENTS FOR SHUTTLE/PAYLOAD ORBITAL OPERATIONS OF THE SPACE TRANSPORTATION SYSTEM

30 June 1978

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Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

Contract NAS 9-14723

Prepared by

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TRW
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Houston, Texas

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CONTENTS

FIGURE

ACRONYMS

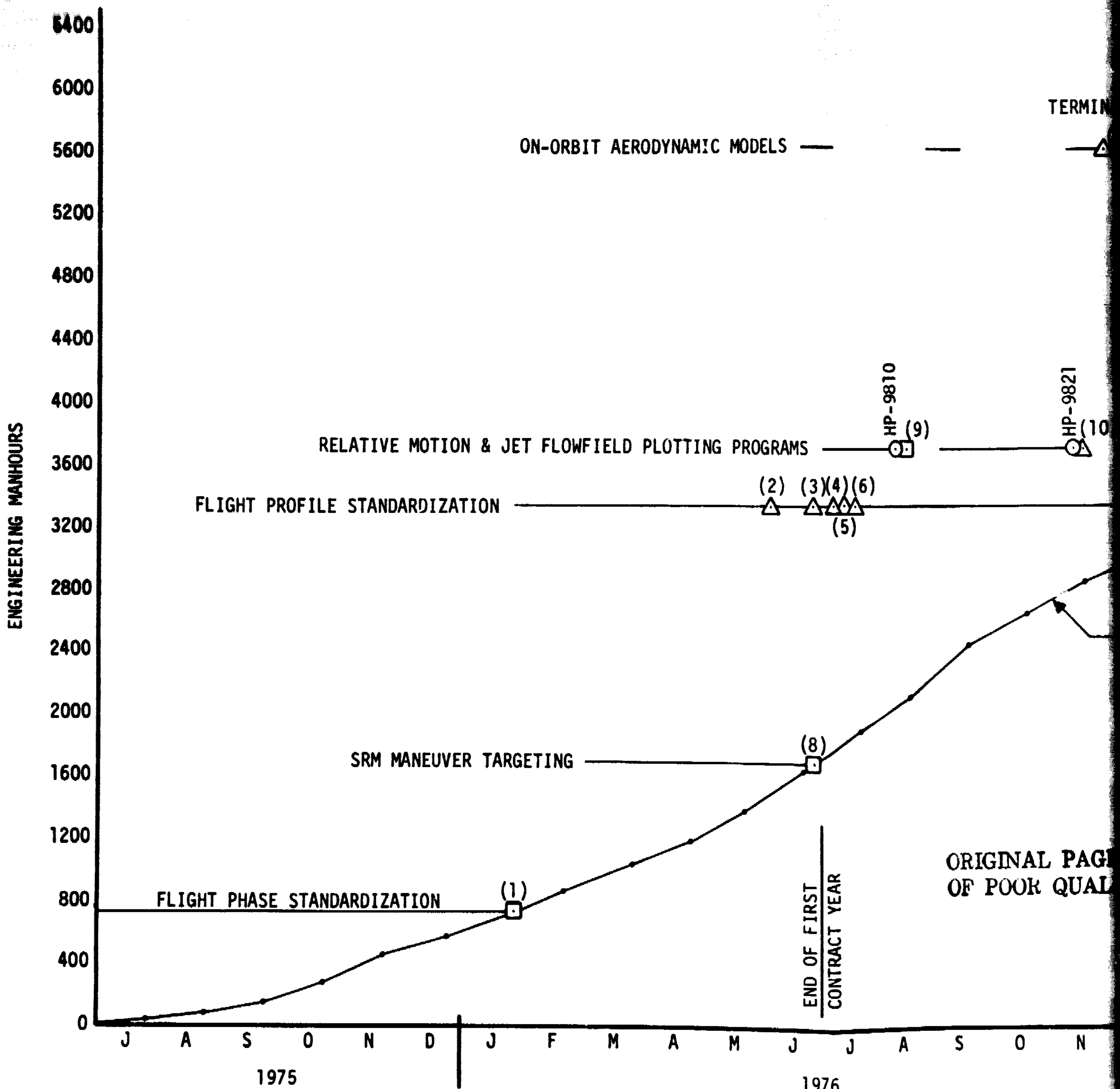
DAP	Digital Autopilot
DTFS	Desk-Top Flight Simulator
IUS	Inertial (originally Interim) Upper Stage
JSC	Johnson Space Center
MPAD	Mission Planning and Analysis Division
OMS	Orbital Maneuvering System
RCS	Reaction Control System
RMS	Remote Manipulator System
SES	Shuttle Engineering Simulator
SMS	Shuttle Mission Simulator
SRM	Solid rocket motor
STS	Space Transportation System

1. INTRODUCTION

The purpose of this report is to summarize the results of studies and software development activities that were conducted in accordance with the original Work Statement (Exhibit "A") of Contract NAS 9-14723. This report is the final deliverable item required by Exhibit "A".

Detailed results of the various activities and studies are contained in the TRW technical reports and memoranda cited as References 1 through 22, and in the JSC documents cited as References 23 and 24. Technical reports and memoranda generated by TRW are represented by square and triangular symbols in Figure 1, which is a graphical history of contract activities and the expenditure of engineering manhours.

The original contract work plan called for engineering effort to be expended essentially at a constant rate over the three year period between 1 July 1975 and 30 June 1978. At the direction of JSC, the work schedule was accelerated sharply in April of 1977, resulting in the depletion of the funds allocated for Exhibit "A" activities in October of 1977. The contract has since been modified by the addition of Exhibit "C", a new work statement which covers activities that are currently in progress. Exhibit "C" activities are not addressed in this report.



FOLDOUT FRAME 1

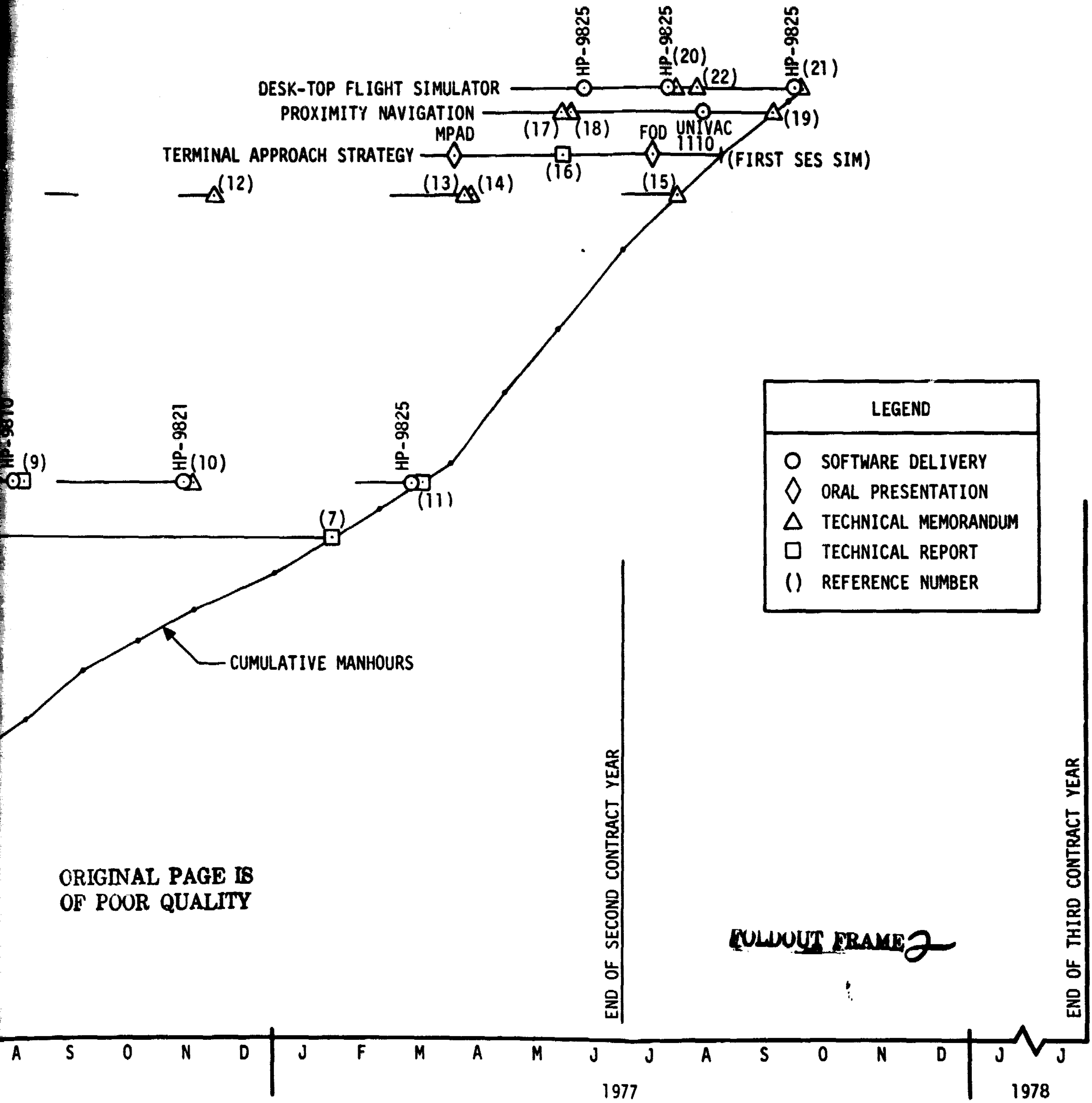


Figure 1. History of Contract Activities

2. MAJOR STUDY TOPICS AND ACTIVITIES

2.1 FLIGHT PHASE STANDARDIZATION

The results of this study are documented in Reference 1. After reviewing Shuttle design characteristics and available data relating to payload configurations and requirements, 27 standard on-orbit flight phase types were defined in generic terms. Each flight phase type was assigned to one of four classes in a hierarchical structure that was devised to clarify the relationships between phase types, and hopefully to provide the basis for a rational modularization of flight planning, training, and software development activities.

2.2 FLIGHT PROFILE STANDARDIZATION

The purpose of this study was to examine the concept of flight profile standardization to determine how it might be applied to reduce the cost of satisfying recurrent flight requirements in the STS operational era. The results are documented in References 2 through 7.

Analysis of available data indicated that STS payloads generally fall into two fundamental categories: (1) primary payloads, whose requirements are so demanding that they will necessarily serve as "drivers" in the design of flight profiles, and (2) companion payloads, whose less demanding requirements are such as to make them candidates for sharing a Shuttle flight with a primary payload.

Flight profiles were designed for three representative primary payload types, and described in terms of the standard phases defined in Reference 1. It was concluded that standardization can be effective in reducing the cost of flight planning and training, provided that a concerted effort is made to achieve it early in the STS operational era. However, it was concluded that unavoidable differences in the on-orbit environment (especially solar illumination) will require a significant degree of flight-to-flight variability in the detailed design of even the simplest profile types, thus emphasizing the need for software that will maximize the efficiency of flight planning personnel.

2.3 MANEUVER TARGETING FOR SOLID ROCKET MOTORS

Unique trajectory design and maneuver targeting problems are posed by the use of solid rocket motors (SRMs) that must burn to propellant depletion once they are ignited. After analyzing the preliminary design specifications of the Interim Upper Stage (IUS), equations and logic were derived for solving the more common types of SRM maneuver targeting problems associated with the delivery of payloads into earth-centered orbits. The equations and logic, which have been implemented (by another contractor) in an upper-stage flight planning program, are documented in Reference 8.

2.4 RELATIVE MOTION AND RCS JET FLOWFIELD PLOTTING PROGRAMS

It became apparent early in the contract period that one of the most important and least understood aspects of Shuttle/payload flight planning had to do with short-range multi-vehicular orbital operations involving the Orbiter and a free-flying payload. The capability to generate accurate graphical portrayals of payload motion relative to the Orbiter and its various jet flowfields was deemed critical for the analysis of such operations. Existing relative-motion computer programs were either inappropriate for the particular problems of interest or too cumbersome to be effective.

To meet the immediate specific needs of the JSC Mission Planning and Analysis Division (MPAD), a rather crude relative motion plotting program was first coded for the HP-9810/HP-9862 calculator/plotter system (Reference 9). The initial capability was upgraded in a program that was coded for the HP-9821/HP-9862 calculator/plotter system (Reference 10). The relative motion of a cylindrical payload is depicted by superimposing orthogonal projections of the payload at regular time intervals on front and side profile views of the Orbiter. Relative positions and attitudes are calculated by integrating the differential equations of translational and rotational motion. Dynamic pressure contours for specified jets of the Orbiter's primary reaction control system (RCS) can also be superimposed on the relative motion plots by a program coded for the HP-9825/HP-9862 calculator/plotter system (Reference 11).

2.5 ON-ORBIT AERODYNAMIC MODELS

A concise aerodynamic drag model was incorporated in the HP-9821 relative motion plotting program described in Section 2.4. For computing drag, the payload was modeled as a flat plate whose area is computed by projecting the payload geometry into a plane normal to its geocentric velocity vector. The Orbiter drag coefficient and the 1962 Standard atmospheric density are calculated from simple curve fit equations. (The Orbiter drag coefficient equation was developed by TRW under another JSC contract.) At the request of the JSC Technical Monitor, an adaptation of the HP-9821 drag model was furnished for incorporation in the JSC Shuttle Engineering Simulator (SES), and the appropriate SES documentation was later reviewed to check for proper implementation (References 12 and 13). In anticipation of a further upgrading of the HP-9821 relative-motion program (currently in progress under Exhibit "C" of the contract), curve fits of the Orbiter's aerodynamic moment coefficients were also derived (References 14 and 15).

2.6 TERMINAL APPROACH STRATEGY FOR PAYLOAD RETRIEVAL/DOCKING

The deployment and retrieval of free-flying satellites and satellite/upper stage combinations are among the most critical STS on-orbit operations. Some payloads will require deployment flight profiles to be designed for a contingency retrieval in the event of a post-deployment checkout anomaly. With this in mind, and taking into account the economic necessity for standardizing flight operations wherever possible, it was considered essential to study the retrieval problem first to establish a basis for assessing the compatibility of deployment techniques with contingency retrieval requirements. (Techniques for deploying and separating IUS/payload combinations from the Orbiter are currently being studied under contract Exhibit "C".)

Because of comparatively severe Orbiter RCS jet plume impingement effects which tend to destabilize and/or contaminate the target satellite, the Gemini/Apollo type of direct approach to a docking or a grappling position is inappropriate for most STS payloads. Recognizing this, JSC has been studying new terminal approach techniques for some time. When this topic was first addressed under this contract, JSC efforts were concentrated on approaches in the plane of the target orbit that involved relative motion parallel to the

Orbiter's Z axis. These techniques require continual adjustment of the relative flight path during the approach (even with perfect initial conditions), and they are comparatively sensitive to range rate estimation errors from the rendezvous radar. In the case of a target that is inertially stabilized, they are also characterized by a continuous rotation of the target relative to the Orbiter's body axes.

A systematic review of available options (Reference 16) led to a conclusion that an out-of-plane tail-first approach is to be preferred over the techniques previously cited. Approaching along a path normal to the orbit plane permits almost identical procedures to be used for the retrieval of payloads whose attitudes are fixed with respect to inertial space or with respect to the rotating local-vertical coordinate system. In either case, the payload's attitude is fixed and its natural motion is nominally rectilinear with respect to the Orbiter's body axes. Approaching tail-first and using a single OMS engine or laterally-opposed +X RCS jets for final braking provides maximum clearance between Orbiter structure and a payload flight path that passes through (and nominally terminates within) the RMS capture envelope. The tail-first approach minimizes plume impingement on the payload during the braking maneuver, and it facilitates visual confirmation of a non-collision course that is fail-safe should the braking impulse not be executed for any reason. Rendezvous radar is not required during the final approach.

Simulated out-of-plane tail-first approaches were run in the SES during the late summer and fall of 1977 (References 23 and 24). Although a need for refinement was apparent, the tests verified the feasibility of the technique.

2.7 PROXIMITY NAVIGATION

"Proximity operations" has been adopted by JSC as the standard terminology to designate short-range on-orbit multi-vehicular operations of any nature. Onboard maneuver-targeting software is being developed to support the flight crew in the execution of certain maneuvers peculiar to this flight regime.

At the time when this topic was addressed, there was a question about whether the standard rendezvous navigation filter (which uses Orbiter-to-target observations to compute estimates of the geocentric inertial states of the two vehicles) would perform adequately to support proximity operations of some types. To support an investigation of this problem by MPAD personnel, a special navigation filter was designed and coded for the HP-9825 calculator and the UNIVAC-1110 computer. The special filter computes estimates of the Orbiter's state vector relative to the target in the rotating local-vertical coordinate system that is used by the proximity operations software for state propagation and maneuver targeting purposes. The filter design is documented, along with the results of various performance tests, in References 17-19.

2.8 DESK-TOP FLIGHT SIMULATOR FOR PROXIMITY OPERATIONS

For many types of proximity operations, the Orbiter is controlled manually by the pilot on the basis of his visual perception of the target's motion. Visual information may come from direct observation through a window, or from a closed-circuit TV camera.

Manual control of the Orbiter is complicated by two primary factors: (1) the general non-linearity of relative motion in a gravity field, and (2) RCS cross-coupling effects which produce extraneous translations and rotations in addition to the nominal responses commanded by hand controller deflections. A real-time man-in-the-loop flight simulator is essential for any realistic evaluation of a technique involving manual flight control. Conventional simulators such as the SES and the SMS are very expensive to build and to operate. Competition for their use is keen, making it difficult to gain access to them.

To provide an economical, readily-accessible simulation capability with sufficient fidelity for at least preliminary evaluation of manual flight control techniques associated with proximity operations, a desk-top flight simulator (DTFS) was developed on the HP-9825/HP-9862 calculator/plotter system (References 20 and 21). The essential components of the DTFS are

(1) a mathematical model of the Orbiter and payload dynamics, (2) a mathematical model of the DAP/RCS flight control system with provisions (by use of the HP-9825's 12 user-definable function keys in conjunction with its "live keyboard" mode of operation) for the pilot to make real-time inputs to the control system, and (3) a display generator to provide a semi-continuous pilot's view (consisting of a snapshot perspective drawing that is updated every 6 seconds) of the apparent position and attitude of the payload, as affected by the dynamics of the multi-vehicular system and by control system inputs.

In connection with the SES simulations cited in Section 2.6, the DTFS proved its value as a filtering device that can be used to enhance the effectiveness of more sophisticated simulators. It has been used to test the feasibility of various approach options preparatory to the proposed docking of an [illegible]S to the Skylab (Reference 22), and to generate propellant consumption and trajectory dispersion statistics that reflect variations in piloting performance. It is believed to have a potential value for preliminary training of flight crews, especially in the area of familiarization with the basic effects of orbital mechanics and RCS cross-coupling. A New Technology report on the DTFS was submitted, in accordance with contract requirements, in July 1977.

3. RECOMMENDATIONS

The following list of recommendations is restricted to major items which are not scheduled for attention under Exhibit "C":

1. As recommended in Reference 7, a systematic plan needs to be implemented for documenting the requirements and design characteristics of standard flight phases and standard flight profiles. Subject to appropriate control procedures, the documentation should be readily updatable so that revisions can be disseminated to all concerned parties on a timely basis.

2. Using the SHAP computer program cited in Reference 25 (or its equivalent), on-orbit aerodynamic coefficients should be computed for the doors-open Orbiter configuration. The aerodynamic coefficient curve-fit equations described in Section 2.5 were based on the data contained in Reference 25, which were computed for a doors-closed configuration. Analytical adjustments were made in some of the curve fits in an attempt to account for the effects of open cargo bay doors; however, the level of confidence in these adjustments is not very high. Since the doors are expected to be opened shortly after orbit insertion on all flights, and not closed again until shortly before the deorbit maneuver, accurate data for a doors-open configuration are needed for most on-orbit simulations.

3. Continued development of the tail-first out-of-plane terminal approach technique is needed to permit an equitable evaluation of its merits relative to alternate methods which have been carried to a higher level of maturity. As pointed out in Section 2.6, the initial SES runs demonstrated the feasibility of the concept, but a need for refinement was evident in some important respects which are detailed in Reference 24.

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