SPACE TUG AUTOMATIC
DOCKING CONTROL STUDY

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DOCKING CONTROL STUDY Final Report
(Lockheed Missiles and Space Co.) 125 p HC
$5.25

FINAL REPORT

CONTRACT NAS 8-29747

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SPACE TUG AUTOMATIC DOCKING CONTROL STUDY

FINAL REPORT

Prepared for
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

Contract No. NASA-29747

Author: J. Wohl

ABSTRACT

This study investigated the docking sensor requirements, the influence of the docking mechanism, and the implications and effects of a docking abort. During the study a digital simulation, which included the primary aspects of the docking maneuver, was developed.
Foreword

This final report of the Space Tug Automatic Docking Control Study was prepared for the National Aeronautics and Space Administration George C. Marshall Space Flight Center by Lockheed Missiles & Space Company, Inc. in accordance with Contract NAS8-29747.

The study effort herein was conducted under the direction of National Aeronautics and Space Administration Study Manager, Mr. Mario H. Rheinfurth; Mr. Homer C. Pack, alternate. The report was prepared by the Lockheed Missiles & Space Company, Inc., Sunnyvale, by Mr. Jack Wohl, LMSC Study Manager. The study results were developed during the period from August 1973, through July 1974.

There are two parts to this report:

(1) Final Technical Report
(2) LOCDOK User's Manual

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Marshall Space Flight Center, Ala. 35812
Telephone (205) 453-2470
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1.1 BACKGROUND

An important mission of the Space Tug is the recovery of satellites at or below synchronous orbital altitudes for return to the Space Shuttle. The docking operation is to be automatic with the possibility of TV remote control available as a backup. The Tug must be able to automatically dock with high probability on the first attempt. This study is intended to provide a basis for designing such a system.

1.2 STUDY OBJECTIVES

(a) Develop terminal docking control strategies and determine the sensor requirements.

(b) Assess the influence of the docking mechanism design on the type and accuracy of sensor data required and the probability of successful docking on the first attempt.

(c) Assess the effects of a missed docking attempt on the Tug propellant consumption and on the payload attitude control system.

(d) Provide documentation of the resultant computer program. This is to include a user's manual, decks and/or tapes, and flow charts sufficient for running the program. Also included will be test cases with the description of inputs and outputs.

1.3 AXES CONVENTIONS

The axes conventions used in this report, the LOCDOK Simulation, and the User's Manual are shown in Figs. 1-1 through 1-4. The numbers shown in the brackets of Fig. 1-4, Vehicle Coordinate System, are the APS engine thrust numbers. In the LOCDOK printout the axial engines (fore-aft)
FIG. 1.1 INERTIAL COORDINATE SYSTEM

FIG. 1.2 EARTH-CENTERED COORDINATE SYSTEM
ASCENDING NODE EPOCH TIME

ASCENDING
NODE
EPOCH TIME

SATELLITE

EQUATOR

0° LONG

R_P

R_A

d

SATELLITE

E = ECCENTRIC ANOMALY

μ = TRUE ANOMALY

FIG. 1-3 ORBITAL COORDINATE SYSTEM

1-3
have a value of 1 for forward thrust. On the plots the axial thrust has the value 9. Which engines are thrusting may be derived from the following algebraic equations.

**LOCDOC Printout**

Axial engine No. = \( l, + \text{thrust} \)

\(- l, - \text{thrust} \)

Lateral engines No. = \[ \begin{bmatrix} l, + z \text{ thrust} \\ -l, - z \text{ thrust} \end{bmatrix} + 3 \begin{bmatrix} + l, -y \text{ thrust} \\ -l, +y \text{ thrust} \end{bmatrix} \]

On the 4020 plots

GUID Eng No. = \[ +/-, \text{thrust} \] + 3 \[ -/+, y \text{thrust} \] + 9 \[ +/-, x \text{thrust} \]

1.4 VEHICLE CONFIGURATION

The Baseline Tug Configuration used in this study is shown in Fig. 1-5.
### 1.5 CONVERSIONS TO SI UNITS*

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<th>From Units</th>
<th>To Units</th>
<th>Constants</th>
</tr>
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<td>Degrees (deg)</td>
<td>Radians (rad)</td>
<td>deg* 0.01745329</td>
</tr>
<tr>
<td>Inches (in.)</td>
<td>centimeters (cm)</td>
<td>in.* 2.54</td>
</tr>
<tr>
<td>Feet (ft)</td>
<td>meters (m)</td>
<td>ft* 0.3048</td>
</tr>
<tr>
<td>Nautical Miles (nmi)</td>
<td>kilometers (km)</td>
<td>nmi* 1.852</td>
</tr>
<tr>
<td>Pounds, force (lb(_f))</td>
<td>newtons (n)</td>
<td>lb* 4.44822</td>
</tr>
<tr>
<td>Mass (slugs)</td>
<td>kilograms (kg)</td>
<td>slug* 14.5939</td>
</tr>
<tr>
<td>Torque (ft-lb(_f))</td>
<td>meter-newtons (m-n)</td>
<td>ft-lb* 1.35582</td>
</tr>
<tr>
<td>Moment of Inertia (slug-ft(^2))</td>
<td>kilogram-meters(^2)(kg-m(^2))</td>
<td>slug-ft(^2)* 1.35582</td>
</tr>
<tr>
<td>Pounds, Mass (lb(_m))</td>
<td>kilograms (kg)</td>
<td>lb(_m)* 0.4532267</td>
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*Conversion Constants from NASA SP-7012, Ref. 14.
2.1 INTRODUCTION

The Standard Characteristics for Analysis is a compilation and specification of the many vehicle and system parameters necessary to simulate and analyze Automatic Docking of the Space Tug.

The characteristics should be considered a living document that will be updated, modified, and added to as the vehicle and subsystem parameters are more definitized.

These Characteristics could be used as the specifications for Space Tug requirements.

The values shown in Section 2.2 are used for the preset data in the LOCDOK Simulation. If these characteristics are changed the preset data should be changed also.
2.2 MASS PROPERTIES

2.2.1 Weight

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<th>(lb)</th>
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<td>Max Retrieval Wt for S&amp;L Tug</td>
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<td>2,570</td>
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<td>Payload Interface</td>
<td>669.0</td>
<td>1,476</td>
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<td>Start Docking Wt</td>
<td>14,810.5</td>
<td>32,678</td>
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<td>Burnout Weight</td>
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<td>Total Propellants &amp; Gases</td>
<td>23,185.2</td>
<td>52,921</td>
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<td>Ignition Weight</td>
<td>26,326.5</td>
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2.2.2 Moments of Inertia and C.G.

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<th>DRY</th>
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<tr>
<td></td>
<td>(slug-ft²)</td>
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<tr>
<td>Pitch (Iyy)</td>
<td>93,742.8</td>
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</tr>
<tr>
<td>Yaw (Izz)</td>
<td>93,437.7</td>
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<tr>
<td>Roll (Ixx)</td>
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<tr>
<td>Tug C.G.</td>
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<th>(slug-ft²)</th>
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<td>Pitch (Iyy)</td>
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<td>Roll (Ixx)</td>
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<td>Tug C.G.</td>
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2.2.3 Attitude Control

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<th>Deadbands (total)</th>
<th>rad</th>
<th>(deg)</th>
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<td>Roll, pitch, yaw</td>
<td>0.008725</td>
<td>0.5</td>
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<td>Moment Arms</td>
<td>m</td>
<td>(ft)</td>
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<td>Pitch, Yaw</td>
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<td>Roll</td>
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# Attitude Control Gains

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<th>n/rad/sec</th>
<th>(lb_f/rad/sec)</th>
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<td>Yaw</td>
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<td>Roll</td>
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<td>699.44</td>
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## 2.2.4 Propulsion

### 2.2.4.1 Engines

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<th>I_min (bit)</th>
<th>I_sp (nominal)</th>
<th>Thrust (nominal)</th>
<th>I_T (Tail off) (nominal)</th>
<th>I_T (Uncert) (3-Sigma)</th>
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<tr>
<td></td>
<td>n-sec</td>
<td>(lb_f/sec)</td>
<td>(lb_f/sec)</td>
<td>n-sec</td>
<td>(lb_f/sec)</td>
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<td>Main Engine</td>
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<td>1,500</td>
<td>66,723.3</td>
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<td>14,234.3</td>
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<td>APS (For-Aft)</td>
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<td>230</td>
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<td>APS (Lat)</td>
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## 2.2.4.2 Propellants, Usable

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<td></td>
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<td>(lb_f/sec)</td>
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<td>Main</td>
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LOCKHEED MISSILES & SPACE COMPANY
2.2.5 Docking Sensor (Scanning Laser Radar) (Ref. 16)

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<td>Data Sampling Rate</td>
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<td>Gimbal Freedom</td>
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<td>Azimuth</td>
<td>0.5235 30</td>
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<tr>
<td>Elevation</td>
<td>0.5235 30</td>
</tr>
<tr>
<td>Gimbal Rates &amp; Acceleration</td>
<td></td>
</tr>
<tr>
<td>Angular Rate (Acq. Aver.)</td>
<td>0.003713 rad/sec; 0.2128 (deg/sec)</td>
</tr>
<tr>
<td>Max Angular Rate (Tracking)</td>
<td>0.001745 1.0 (deg/sec)</td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>N/A</td>
</tr>
<tr>
<td>Acquisition Range (99% probability of acquisition)</td>
<td>143.72 km; (77.6) nmi**</td>
</tr>
<tr>
<td>Acquisition Scan Pattern</td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
<td>rad (deg)</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.5235 30</td>
</tr>
<tr>
<td>Search Frame Time</td>
<td>1.41376 sec</td>
</tr>
<tr>
<td>Track Frame Time</td>
<td>0.064 sec</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>rad (deg)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.0001745 0.1</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>ft</td>
</tr>
<tr>
<td>Angle Resolution</td>
<td>rad (deg)</td>
</tr>
<tr>
<td>Range Accuracy (3-sigma Smoothed Data)</td>
<td>0.01% of R</td>
</tr>
<tr>
<td>Angle Accuracy (3-sigma Smoothed Data)</td>
<td>0.0008725 rad; .05°</td>
</tr>
</tbody>
</table>

Both Receiver and Scintillation noise are modeled as a function of Range (R).

**Per Telecon with ITT 143.72 km; (77.6 nmi) can be achieved.
Receiver Noise (at 143.72 km; 77.6 (nmi)

Range (Std. Dev.) ($\sigma_R$) 

$\sigma_R = 23.8355$

AZ, EL (Std. Dev.) ($\sigma_R$) 

$\sigma_R = 0.290855$

Noise constant below 0.3048 m (1 ft) and beyond 143.72 km (77.6 nmi)

Scintillation Noise (at 0.3048 m; 1 (ft))

AZ, EL (Std. Dev.) ($\sigma_S$) 

$\sigma_S = 6.171(R)^{-1}$

Noise constant below 0.3048 m; 1 (ft) and beyond 143.72 km (77.6 nmi)

2.2.6 Start Docking Guidance Accuracy (3-sigma)

<table>
<thead>
<tr>
<th>Position</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km</td>
</tr>
<tr>
<td>Tangential</td>
<td>55.56</td>
</tr>
<tr>
<td>Radial</td>
<td>59.26</td>
</tr>
<tr>
<td>Normal</td>
<td>59.26</td>
</tr>
</tbody>
</table>

2.2.7 Payload Position Uncertainty (3-sigma)

Position, each axis 1.852 km (1 nmi)

2.2.8 Docking Mechanism Requirements (3-sigma)

- Docking Axis Miss Distance: 0 to 0.3048 m (1.0 ft)
- Miss Angle: $\pm 0.05235$ rad ($\pm 3$ deg)
- Long. Velocity: $0.0348$ m/sec (.1 ft/sec) to 0.3048 m/sec (1.0 ft/sec)
- Lateral Velocity: 0 to 0.09144 m/sec (0.3 ft/sec)
- Angular Velocity: 0 to 0.001745 rad/sec (1.0 deg/sec)

2.2.9 Autonomous Navigation Update (3-sigma)

Position, Each Axis 5.858 km; (3.163 nmi)

*Must be divided by 217,945.9 m (715,045.6 ft) for input to LOCDOK.
Section 3
LITERATURE SURVEY

3.1 INTRODUCTION

A literature survey was made at the beginning of the contract. LMSC's Technical Information Center interrogated the DDC and NASA data bases, classified as well as unclassified. In addition, LMSC's Dialog data base was surveyed.

The following Descriptors singly and in combination were used:

- Spacecraft
- Guidance
- Rendezvous
- Navigation
- Unmanned
- Docking
- Mechanism
- Sensors
- Control Systems

3.2 SURVEY

DOD UPPER STAGE/SHUTTLE SYSTEM

McDonnell-Douglas, Huntington Beach
AD-903 092L Unc. Vol. III

Report No. 19DC-03702 - Vol. 1
Contract F04701-72-C-0304
SAMSO TR-72-202-Vol, 1,3
PAYLOAD HANDLING CAP OF THE STS
AD-900 346L
Office of the Assistant for Study Support, Kirtland AF Base
Report No. OAS-TR-72-3

FEAS. STUDY, VOL. IV, SYSTEM DESIGN
Rockwell International AD-889 574L
OOS (Chemical)
Append. B - Avionics Study
Report No. SD-71-730-4B
Contract PO4701-71-C-0171
SAMS TR-71-238 Vol. 4B

TIME-LINE INFO FOR MISSIONS INTO STATIONARY ORBITS
AD-876 5026 Aerospace
Report No. TDR-0059 (6770-01)-2
Contract PO4701-70-C-0059

TERMINAL REND. CONSIDERATIONS FOR THE STS
AD-875 194L
Aerospace
Report No. TDR-0059 (6758-07)-6
Contract PO4701-70-C-0059

RENDEZVOUS TRAJ. VOL. I
AD-722 890
Report No. DDC-TAS-70-85-1
AD-515 440

DOD IMPACT ON SHUTTLE SYSTEM DESIGN STUDY, VOL. IX - SUPPLEMENTARY STUDY TASK
AD-516-277L
Rockwell International
CONFIDENTIAL Report
No. SD-71-142-9
Contract: NAS9-10960
SAMS TR-71-123 Vol. 9 3-2
GUIDANCE, NAVIGATION, AND CONTROL FOR AUTO REND, DOCK AND SEPARATION OF S-11 DERIVATIVE VEHICLES

SD-73-SA-0009
Rockwell International
Contract NAS7-200

REND. AND DOCK GUID ALG ANALYSIS & DER OF EQUATIONS OF MOTION FOR FLEX APPENDIX CLUSTERS OF GRAVITY

Tag IBM No. 72-228-062

RESPONSE OF FLEXIBLE SPACE VEHICLES TO DOCKING IMPACT

Bodley, C. S., and A. C. Park
Final Report
Contract NAS8-21280, Martin Corp.

SPACE SHUTTLE VEHICLE AUTOMATIC DOCKING STUDY

Author: Blanchard, E. P. Hutchinson, R. C. Johnson, I. B.
Final Report
Oct 71 84p
Contract: NAS9-10268, DSR Proj. 55-40800

AUTOMATIC RENDEZVOUS & DOCKING FINAL REPORT

Report No: NASA-CR-103037
A1984F1 Flid: 22A, 84A STAR0907
May 70 208p
Contract: NAS8-23973

LATCHING MECHANISM PATENT APPLICATION

North American Rockwell Corp., Los Angeles, Calif.
Author: Cobin, J. C., Rhodes, L. L.
A017282 ELD: 13E, 22B, 922, 944 STAR0808
21 Nov 69 33p
Contract: NAS9-150 3-3
AUTOMATIC RENDEZVOUS IN SPACE

Foreign Technology Div Wright-Patterson AFB Ohio (141600)
Author: Legostaev, V. P., Raushenbakh, B. V.
6105E1 FLD: 22A, 22C (USGRDR6913)
5 Dec 68 31
Report No. PTD-HT-23-1346-68
by D. Koolbeck.

SYMPOSIUM ON AUTOMATIC CONTROL IN SPACE (2nd) (SELECTED MISSIONS)

Foreign Technology Div Wright-Patterson AFB Ohio (141600)
5732B3 FLD: 22B USGRDR6908
14 Jun 68 65p
Report No. PTD-MT-24-127-68
Edited machine trans. of Symposium on Automatic Control in Space (2nd)
Vienna, 4-8 Sep 67 pl-43

DOCKING IN SPACE A COMPLEX PROBLEM

Author: Noviko, Yu., Pedorov, B.
5635A3 FLD: 22A USGRDR6906
15 Jun 68 10p
Trans. of Aviatsiya i Kosmonavtika (USSR) n2 p53-56 1968.

A NEW STAGE IN THE CONQUEST OF SPACE. BRILLIANT EXPERIMENT SEES AUTOMATIC DOCKING OF TWO SPACECRAFT IN ORBIT

Foreign Technology Div Wright-Patterson AFB Ohio (141600)
5412B4 FLD: 22B USGRDR6903
6 Dec 67 8p
Report No. PTD-HT-23-1606-67
Edited trans. from Pravda, Moscow (USSR) p3, 1 Nov 67, by R. Zeccola

3-4

LOCKHEED MISSILES & SPACE COMPANY
RENDEZVOUS IN SPACE. HOW THE AUTOMATIC SATELLITES FOUND EACH OTHER IN ORBIT

Foreign Technology Div Wright-Patterson AFB Ohio (141600)
Author: Marinin, Yuri
5373C1 FLD: 22A USGRDR6902
6 Dec 67 7p
Report No. FTD-HT-23-1605-67
Edited trans. from Pravda, Moscow (USSR) p2, 2 Nov 67, by R. Zeccola

WORLD'S FIRST AUTOMATIC DOCKING IN SPACE. TWO SATELLITES IN COMMON ORBIT

Foreign Technology Div Wright-Patterson AFB Ohio (141600)
5371A1 BLD: 22A, 22B USGRDR6902
6 Dec 67 5p
Report No. FTD-HT-23-1604-67
Edited trans. from Pravda, Moscow (USSR) pl, 31 Oct 67, by R. Zeccola

AUTOMATIC DOCKING IN SPACE AND ITS RELATION TO THE THEORY AND PRACTICE OF AUTOMATIC CONTROL

Techtron Corp, Glen Burnie, Md.
Author: Raushenbakh, V. K.
Avtomaticheskiya Stykovka W Kosmose I Yeye Sv yaz's Teoriyey I
Practikoy Avtomaticheskogo Upravleniya
5215B3 FLD: 22A STAR0621
Sept 68 8p
Report No. NASA-TT-F-11939
Contract: NASW-1695
1968 Coll 8p Tran Transl. Into English of Paper A/Conf. 34/Iv. 10,
Presented at the United Nations Conf. on the Exploration and Peaceful
Uses of Outer Space, Vienna, 14-27 Aug 1968

SPACE SHUTTLE GUIDANCE, NAVIGATION AND CONTROL DESIGN EQUATIONS VOLUME 3 ORBITAL OPERATIONS

National Aeronautics and Space Administration Manned Spacecraft Center,
Houston, Tex.
A4995K3 FLD: 22A, 84A STAR1016
1 Dec 71 550p
Misc 0 revised

LOCKHEED MISSILES & SPACE COMPANY
FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON AFB OHIO (141600)

Author: Lebedev, A. A., Sokolov, V. B.
A340314 FLID: 22A, 22C, 84A, 84D USGRAD7203
30 Aug 71 503p
Report No. FTS-MT-24-26-71
Project: AF-4160
Task: 416010, DIA-T70-16-1
Edited machine trans. of mono. Vstrecha na Orbite, Moscow, 1969 pl-366, by Charles T. Ostertag

PROJECT/SPACE SHUTTLE - SPACE SHUTTLE GUIDANCE, NAVIGATION AND CONTROL DESIGN EQUATIONS. VOLUME 3 - ORBITAL OPERATIONS

NASA, MSC, Houston, Tex.
A3062A4 FLID: 17C, 84A STAR0319
15 Apr 71 227p

APOLLO SPACECRAFT SYSTEMS ANALYSIS PROGRAM. ANALYSIS OF RENDEZVOUS RADAR PEARL FLIGHT TEST DATA

TRW Systems Group, Redondo Beach, Ca.
Author: Dobby, S. D., Doty, M. G.
585514 FLID: 22B STAR0707
4 Nov 68 46p
Contract: NAS9-8166

AUTONOMOUS CONTROL OF A SPACECRAFT IN THE PROBLEM OF RENDEZVOUS WITH A MOVING OBJECT

Foreign Tech Div Wright-Patterson AFB Ohio (141600)
Author: Bogomolov, A. I.
5483E4 FLID: 22C USGRDRA6904
16 Apr 68 9p
Report No. FTD-ET-23-229-68
Edited trans. of Aviatsionnyi Inst, Kazan Trudy (USSR) n89 p41-47 1965, by J. Miller

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NAVIGATION SYSTEMS OF SPACECRAFT

JPL, Calif Inst of Tech, Pasadena. Terra-space Corp., Malibu, Ca
Author: Kirst, M. L., Seleznyev, V. P.
435313 FLD: 17G, 22B STARD 606
1965 33p
Report No. NASA-CR-92568
Contract: NAS7-100
Transl into English from Voyennoye Izd. Min. Oborony USSR Moscow
1965 Prepared for JPL

SIXTH AAP-4 UNMANNED RENDEZVOUS MEETING AT MSC, JUNE 27, 1968
68XB 7673* NASA-CR-96026 NASW-417 68/07/05 4 pages
A/Guffee, C. O.
Bellcomm, Inc., Washington, D. C.

POSSIBLE APPROACH TO PHASING FOR UNMANNED RENDEZVOUS, CASE 610
68XB 3909* NASA-CR-93608 NASW-417 68/02/29 9 pages
A/Martersteck, K. E.
Bellcomm, Inc., Washington, D. C.

THE PROBLEM OF DOCKING WITH A PASSIVE ORBITING OBJECT WHICH POSSESSES ANGULAR MOMENTUM
71X10 921*# Issue 4 Page 177 Category 30 NASA-CR-122853
(Development and Analysis of Techniques for Retrieving Uncooperative Spinning Objects in Space Environment)
A/Keplam, M. E.
Pennsylvania State University, University Park. (Dept. of Aerospace Engineering)

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LOCKHEED MISSILES & SPACE COMPANY
UNMANNED RENDEZVOUS APPLICATIONS FOR SPACE RESCUE
73Al 1156 Issue 1 Page 105 Category 30 71/00/00 5 pages
A/Hateley, J. C. (LMSC, Sunnyvale, Ca)
International symposium on space technology and science, 9th
Tokyo, Japan, May 17-22 1971
Proceedings (A73-11101 01-31) Tokyo, AGNE Publishing, Inc.
1971, p. 557-561

CONTRIBUTIONS TO THE STUDY OF A EUROPEAN INTERORBITAL TUG
71A3 70309 Issue 19 Page 3150 Category 31 71/00/00 12 pages
In Italian
(European Unmanned Interorbital Tug, Investigating Configurations
Structure, Hookup System, Docking and Propellant Supply)
A/Porru, M. (AA/Fiat S.P.A., Division Aviazione, Turin, Italy
Rome, Rassegna Internazionale Elettronica Unclear
Teleradiocinematografica, convention sponsored by the Ministero Degli
Affari Esteri and the Associazione Industrie Aerspaziali

INSTITUTE OF NAVIGATION, NATIONAL SPACE MEETING ON SPACE SHUTTLE-SPACE
STATION—NUCLEAR SHUTTLE NAVIGATION
71A3 5051 Issue 17 Page 2772 Category 21 71/00/00 540 pages
Proceedings (Space Shuttle, Space Station and Nuclear Shuttle
Navigation-Conference, Huntsville, Ala., Feb 1971)

AUTOMATIC CONTROL IN SPACE 3, INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL
71A1 9526 Issue 7 Page 1154 Category 21 70/00/00 815 pages
International Conference, 3rd Toulouse, France, March 2-6, 1970

UNMANNED RENDEZVOUS, STATION KEEPING, AND DOCKING FOREXTRAVERICULAR SPACE
ACTIVITIES
72W7 5159 68/00/00 22 pages
A/Puri, N. N. B/Lambert, A. I. C/Gido, J. F.
General Electric Co., Philadelphia, Pa (Missile & Space Div)

FIFTH AEROSPACE MECHANISMS SYMPOSIUM
72WL 3391 Issue 4 Page 485 Category 15 NASA-SP-282 71/00/00
(Conference of Structural Design Principles and Mechanical Engineering
Methods for Aerospace Mechanisms Used in Orbital and Space Flights)

3-8

LOCKHEED MISSILES & SPACE COMPANY
RENDEZVOUS IN SPACE. HOW THE AUTOMATIC SATELLITES FOUND EACH OTHER IN ORBIT

A/Martinin, Y.
Air Force Systems Command, Wright-Patterson AFB, Ohio
(Foreign Technology Div.)

APPLICATIONS OF RADAR TO SPACECRAFT AND SPACEFLIGHT

A/Colwell, R. G.; B/Dickerson, S. L.: C/Paul, A. N.
Houston University, Texas

National Aeronautics and Space Administration, L. B. Johnson Space Center, Houston, Texas
Presented at the Southwestern Inst of Elec and Electron Engr, 1 April 1966
Section 4
DOCKING CONTROL STRATEGIES

4.1 INTRODUCTION

Docking Control strategies must be formulated for the seven autonomous docking phases shown in Table 4-1. The strategies not only have to encompass the events shown in the table, but also selection of a data filter.

To completely define all the strategies would require knowledge of the Tug's Avionics Configuration, mission definition, and operational constraints. One possible Avionics configuration is shown in Fig. 4-1. Note that this configuration has the equipment needed for autonomous navigation.

For the following discussion, refer to Table 4-1.

4.2 Phase 1 - Rendezvous Injection Burn

The first phase for docking begins after the rendezvous injection burn, which should place the Tug at the nominal aim-point. Calculation of the nominal aim point is discussed in Section 5. The position of the aim-point must consider the aspect of the sun, moon, or earth with respect to the field-of-view of the docking sensor. If a docking sensor is selected that is in the visual or infrared spectrum an additional constraint would be to have the payload sun-illuminated.

It would be advantageous to have the Tug perform an autonomous navigation update at this time to reduce the uncertainty in its position and reduce the sensor FOV requirements, see Section 5. If the Tug missions include multiple payload servicing or deployment, then the navigation update would be required if the Tug's autonomy level is I or II.
4.3 Phase 2 - Reorientation

The Tug's attitude after the injection burn will normally require reorientation of the Tug to point the center of the sensor's search pattern at the center of the uncertainty volume of the payload.

The primary decision for this phase would be the time allotted for the maneuver. The longer the reorientation time the less APS propellant would be used.

4.4 Phase 3 - Acquisition of the Payload

The primary strategy to formulate during this phase would be if the payload was not acquired. Several alternatives are shown in Table 4-1.

If the payload is acquired but there is a possibility that the Tug might impact the payload in a short time, or the Tug might move out of the acquisition range of the sensor, an immediate evaluation must be made. LOCDOK performs a rapid data taking and evaluation after lock-on to either stop the motion of the Tug or reverse its velocity if it is moving away from the payload.

4.5 Phase 4 - Gross Transfer to the Docking Axis

Given the docking axis in the payload orbital coordinate system and knowing the Tug's state vector relative to the payload from the sensor, the Tug can now compute a gross transfer to the docking axis. It is interesting to note that the Tug's state vector is now known very accurately as the payload position is known to ± 1.852 (1 μm) three sigma.

The control strategy in LOCDOK for this phase checks to see that the Tug's trajectory to the docking axis does not violate the required miss distance threshold (see Fig. 4-2). The trajectory then is calculated so as to terminate the gross transfer beyond the minimum gross transfer distance specified. The transfer distance is selected so that the Tug can null all positions and velocity errors normal to the docking axis before it reaches the stand-off range. The average velocity toward the docking axis is computed so that the Tug will reach the axis in a maximum specified time.
During the Tug's transfer to the axis the sensor is always pointed toward the payload (1) to keep the payload within the FOV of the body mounted sensor and (2) to automatically acquire the docking aid on the payload after the final gross transfer burn.

Mid-course corrections are periodically made to correct trajectory errors.

The final gross transfer burn is computed, allowing for the long thrusting period, so that the docking axis is not crossed. The velocity along the docking axis should be that specified by mission requirements.

The transfer to the docking axis is considered complete if the docking aid is within the FOV of the docking sensor. If it is not the Tug would make an additional fast transfer to the axis maneuver. In the event that the docking aid is not acquired, (the attitude of the payload has drifted the docking aid out of the FOV of the sensor). A means for acquiring the docking aid must be implemented. One method of accomplishing this would be to have the Tug circumnavigate the payload until the aid is acquired. At present LOCDOK does not have this capability. However, a circumnavigation simulation has been developed by LMSC and could be integrated into LOCDOK at a later date. Capability for this addition are provided in LOCDOK.

It should be understood that if the payload is rotating rapidly, during any phase of docking, the docking attempt must be completely aborted.

4.6 Phase 5 - Transfer down the Docking Axis

The basic guidance strategy for Phase 5 is to null the position and velocity errors normal to the docking axis while maintaining the velocity along the axis. This portion of the guidance uses an exponential logic to minimize propellant usage. The rapidity of convergence is controlled by the operator who can select the exponent, G17 in the input dictionary.
The final burn down the docking axis normally reduces the Tug's velocity to that permitted by the docking mechanism and the potential abort maneuver.

Note that the retro burn has to be made far enough from the Tug so that thruster impingement does not disturb the payload. From the retro burn point on, all forward thrusting engines must be disabled because of impingement.

4.7 Phase 6 - Evaluation at the Stand-off Point

At the stand-off point the Tug to payload position, velocity, and attitude is evaluated. If the tolerances dictated by the docking mechanism are exceeded the Tug should abort the attempt. The stand-off point selection is detailed in Section 7.

There should be some provision made to inspect the payload docking mechanism to see that it is not obstructed or damaged.

4.8 Phase 7 - Coast to Latch-Up

During this phase all thrusters must be disabled except for an emergency abort capability. It should be understood that an abort at this time will severely disturb the payload and may make future docking attempt impossible.
4.9 DATA FILTERING

4.9.1 Introduction

As all sensor measurements are noisy, some method of data filtering must be employed to determine the best estimate of the payload state vector with respect to the Tug.

This section summarizes known results in linearized and linear estimation theory. The classical least squares maximum likelihood version of the non-linear estimation problem is outlined and the sequential version of the optimum filtering solution (as derived by Kalman). The Kalman equations have the advantage that dynamic noise in the model is easily handled, but both the least squares version and the Kalman equations can be used with any deterministic model.

A six-by-six sequential Kalman was selected for the Tug data filtering as being the best compromise for on-board processing. The Tug has knowledge of its accelerations from on-board instrumentation and it is assumed that the payload would not maneuver.

This data filter has been incorporated in the LOCDOK simulation in subroutine HEST. For additional details see Reference 12 and 13.

4.9.2 Notation

In general, lower case letters in the equation notations (i.e., u, v, x, and z) denote column vectors while upper case letters (i.e., A, B, F, G, H, and E) denote matrices. The components of a matrix A and vector u are designated by subscripts as $A_{ij}$ and $u_j$. The letter I represents the identity
matrix. The superscript prime, as in $A'$ or $u'$, will denote the transpose of the matrix or the transpose of a column vector (which becomes a row vector). The product of a column vector and a row vector, such as $xz'$ is a matrix. The symbol $E$ represents the expected value so that $E(A)$ represents the expected value of the quantity $A$. The subscript -1 as in $A^{-1}$ means the inverse of the matrix $A$. In all cases it will be assumed that the inverse of the matrix exists, although, quite often, the inverse can be replaced by a pseudo-inverse or generalized inverse without changing the results.

4.9.3 Classical Least Squares

A set of equations used to model nonlinear estimation for a deterministic system can be written as shown below where $N$ is the number of measurements, $z_k$ is the $l \times 1$ vector representing the actual measurements, $w_k$ is the $l \times 1$ vector representing the uncorrelated noise on the measurements, $x$ is the $m \times 1$ vector representing the state of the system, $h_k(x)$ is an $l \times 1$ vector representing perfect measurements, and $R_k$ is the $l \times l$ covariance matrix of the noise

$$z_k = h_k(x) + w_k$$

$$\text{cov } w_k = R_k \quad \text{for } k = 1, 2, \ldots, N$$

It will be assumed the noise has zero mean and it is uncorrelated from one measurement to the next.

$$E[w_k] = 0$$

$$\text{cov } [w_j w_k] = 0 \quad j \neq k$$

The best estimate of the state $\hat{x}$ can be written as shown below, where $H_k$ is the $l \times m$ matrix of partial derivatives and $\hat{x}_0$ is the initial nominal value of the state
The inverse of $M$ is the covariance of the error in the estimate. If the model is linear, the nonlinear function $h_k(\hat{x}_0)$ is replaced by its linear equivalent $H_k\hat{x}_0$ and the expressions involving $\hat{x}_0$ cancel out as shown below.

$$\hat{x} = \hat{x}_0 + M^{-1} \left\{ \sum_{k=1}^{N} H'_k R_k^{-1} \left[ z_k - h_k(\hat{x}_0) \right] \right\} \quad (4-3)$$

where $M = \sum_{k=1}^{N} H'_k R_k^{-1} H_k$

$$H_k = \partial h_k(x)/\partial x$$

$$\text{cov}(x - \hat{x}) = M^{-1}$$

If there is prior information that the state $x$ has a value $x_0$ with covariance $P_0$, it can be included in the above analysis by extending the sum so it includes $k = 0$ and defining $z_0 = \bar{x}_0$, $H_0 = \text{identity}$, and $R_0 = P_0$.

4.9.4 Sequential Kalman Filter

For the discrete version of the linear estimation problem, the system to be estimated can be described by the following set of matrix difference equations.

$$x_{k+1} = \Phi_{k+1} x_k + u_k \quad (4-5)$$
The linear measurements obtained from the system are given by another set of matrix equations.

\[ z_k = H_k x_k \cdot w_k \text{ for } k = 1, 2, \ldots, N \]  

(4-6)

The matrices \( \Phi \) (transition matrix) Tables 4-2 and 4-3 and \( H \) (output matrix) Table 4-4 represent known quantities which can change from one measurement to the next. The vector \( x \) represents the estimated state of the system while the vector \( z \) represents known measurements. The vectors \( u \) and \( w \) are not known exactly, but are zero mean independent random variables with known covariance. The variable \( u \) represents random changes in the state (dynamic noise) while the variable \( w \) represents random changes in the measurements (measurement noise). The subscript \( k \) represents the value of the quantities at the time of the \( k \)th measurement. If the dynamic noise \( u \) is identically zero for all time, the system is said to be "deterministic." The covariances of the zero mean dynamic noise and measurement noise are shown below:

\[ E(u_j u'_k) = Q_k \text{ if } j = k \text{ and zero otherwise} \]  

(4-7)

\[ E(v_j v'_k) = R_k \text{ if } j = k \text{ and zero otherwise} \]

\[ E(u_j v'_k) = 0 \]

Most physical systems will involve nonlinear equations, but it is assumed the above set of linear equations can be obtained by linearizing about some nominal values for the state and the measurements. It may be that the physical system is governed by a set of linear (or linearized) differential equations although the measurements will take place at discrete times. In that case, the original system differential equations must be integrated to obtain the required difference equation relating the change in state from one measurement to the next. Conversely, under certain conditions, in the limiting case as time between measurements goes to zero, the discrete system will approach a continuous system.

LOCKHEED MISSILES & SPACE COMPANY
<table>
<thead>
<tr>
<th>( \rho \text{(rad)}_t )</th>
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<th>( \rho \text{(rad)}_t )</th>
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<td>( \rho \text{(CT)}_0 )</td>
<td>( \rho \text{(rad)}_t )</td>
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</tr>
<tr>
<td>( \rho \text{(CT)}_0 )</td>
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<td>( \rho \text{(CT)}_0 )</td>
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</tr>
<tr>
<td>( \rho \text{(rad)}_0 )</td>
<td>( \rho \text{(IT)}_0 )</td>
<td>( \rho \text{(CT)}_0 )</td>
<td>( \rho \text{(IT)}_0 )</td>
<td>( \rho \text{(CT)}_0 )</td>
<td>( \rho \text{(IT)}_0 )</td>
</tr>
<tr>
<td>( \rho \text{(rad)}_t )</td>
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<td>( \rho \text{(rad)}_t )</td>
<td>( \rho \text{(rad)}_t )</td>
<td>( \rho \text{(rad)}_t )</td>
<td>( \rho \text{(rad)}_t )</td>
</tr>
</tbody>
</table>

\[ \Phi \]
# Table 4-3

**Transition Matrix**

\[
\begin{bmatrix}
1.0 & -6 \sin \omega t + 6 \omega t & 0.0 & \frac{4}{\omega} \sin \omega t - 3t & -2 \cos \omega t + 2 & 0.0 \\
0.0 & 1.0 & 0.0 & \frac{2}{\omega} \cos \omega t - 2 \omega t & \frac{1}{\omega} \sin \omega t & 0.0 \\
0.0 & 0.0 & 1.0 & 0.0 & 0.0 & t \\
0.0 & -6 \omega \cos \omega t + 6 \omega t & 0.0 & 1.0 & 2 \sin \omega t & 0.0 \\
0.0 & 3 \omega \sin \omega t & 0.0 & -2 \sin \omega t & 1.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1 \\
\end{bmatrix}
\]
TABLE 4-4
MATRIX OF PARTIAL MEASUREMENTS WITH RESPECT TO THE ORBITAL FRAME

\[
H = \begin{bmatrix}
\frac{\partial S}{\partial \text{rad}} & \frac{\partial S}{\partial \text{IT}} & \frac{\partial S}{\partial \text{CT}} \\
\frac{\partial E_l}{\partial \text{rad}} & \frac{\partial E_l}{\partial \text{IT}} & \frac{\partial E_l}{\partial \text{CT}} \\
\frac{\partial A_z}{\partial \text{rad}} & \frac{\partial A_z}{\partial \text{IT}} & \frac{\partial A_z}{\partial \text{CT}}
\end{bmatrix}
\]

\[
H = \begin{bmatrix}
\text{rad}/S & \text{IT}/S & \text{CT}/S \\
\cos E_l/S & -(\text{IT} \tan E_l)/S^2 & -(\text{CT} \tan E_l)/S^2 \\
0 & -\text{CT}/(\text{CT}^2+\text{IT}^2) & \text{IT}/(\text{CT}^2+\text{IT}^2)
\end{bmatrix}
\]

where

\[
S = \text{range}
\]

\[
\text{Rad} = \text{radial position difference}
\]

\[
\text{IT} = \text{In-track position difference}
\]

\[
E_l = \text{Elevation angle}
\]

\[
A_z = \text{Azimuth angle}
\]
The optimum estimate will be the linear estimate which minimizes the mean square error. Calculating the estimate requires knowing the mean and covariance of all the random variables of interest, but no higher moments. If all the random variables have a normal probability distribution, the estimate will be the conditional mean of the state given the measurements. Sometimes the estimate is also called the Maximum Likelihood estimate because it maximizes the conditional probability distribution.

Let \( \hat{x}_{j/k} \) denote the optimum estimate of the state \( x_j \) given all the measurements up to \( z_k \). If \( j \) is greater than or equal to \( k \), it is called filtering and prediction. If \( j \) is less than \( k \), it is called smoothing. The error in the optimum estimate is the difference between the actual value of the state and the estimate. The covariance matrix of the error, \( P_{k/j} \), is defined:

\[
P_{k/j} = E(x_k - x_{k/j})(x_k - \hat{x}_{k/j})'
\]

The sequential version of the optimum filtering solution, as derived by Kalman, can be written as shown below where \( B_k \) is the gain on the Kalman filter.

\[
\hat{x}_{k/k} = \hat{x}_{k/k-1} + B_k(z_k - H_k \hat{x}_{k/k-1})
\]

\[
B_k = P_{k/k-1} H_k (H_k P_{k/k-1} H_k' + R_k)^{-1}
\]

\[
\hat{x}_{k+1/k} = \Phi_{k+1} \hat{x}_{k/k}
\]

The covariance matrix \( P \) can also be calculated sequentially:

\[
P_{k/k} = (I - B_k H_k) P_{k/k-1}
\]

\[
P_{k+1/k} = \Phi_{k+1} P_{k/k} \Phi_{k+1}' + Q_k
\]

The initial conditions for the filtering solution are based on the a priori information, which is that the state variable \( x_1 \) has a known mean, \( \bar{x}_0 \), and covariance \( P_0 \). 

4-12

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For computational reasons, it is necessary that the matrix \( \tilde{P}_0 \) be non-singular. If the actual a priori information is not sufficient to make \( \tilde{P}_0 \) non-singular, usually it can be modified empirically, by trial and error, to make it non-singular without having a substantial effect on later calculations.

An alternative sequential version of the optimum filtering solution makes use of two relations:

\[
\begin{align*}
P_{k/k}^{-1} &= P_{k/k-1}^{-1} + H_k R_k^{-1} H_k^T \\
\hat{x}_{k/k} &= P_{k/k-1}^{-1} \hat{x}_{k/k-1} + H_k R_k^{-1} z_k
\end{align*}
\]

These relations arise naturally when using the classical maximum likelihood derivation. The first relation can be proved by multiplying \( P_{k/k}^{-1} \) by \( P_{k/k} \) to get the identity; the second, by showing that

\[
B_k = P_{k/k} H_k' R_k^{-1}
\]
<table>
<thead>
<tr>
<th>PHASE 1</th>
<th>PHASE 2</th>
<th>PHASE 3</th>
<th>PHASE 4</th>
<th>PHASE 5</th>
<th>PHASE 6</th>
<th>PHASE 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rendezvous Burn</td>
<td>Reorientation</td>
<td>Acquisition of Payload</td>
<td>Cross Transfer to Docking Axis</td>
<td>Transfer Down Docking Axis</td>
<td>Eval., at the Standoff Point</td>
<td>Coast to Latchup</td>
</tr>
</tbody>
</table>

**GUIDANCE ERRORS**
- ATT ERRORS
- AIM POINT CONSIDERATIONS
  - Sun Illum of Payload
  - No Sun, Moon, or Earth in FOV
  - Safety: No Possible Impact of Payload
  - Performance Optimization

**COMPUTATION OF ATTITUDE COMMANDS TO POINT CENTER OF VOY AT CENTER OF UNCERTAINTY VOL. FOR PAYLOAD**
- Rotation of TUG
- Check for Sun, Moon, Earth in FOV

**ACQUISITION**
- Range vs Guid ACC
- FOV vs Guid & ATT ACC
- Range vs Payload Illuminance
- Multiple and Spurious Targets
- Payload Scintillation (Amplitude)
- Aspect Angles & Optimizing Acq., i.e., Orient Along Large Disp. Axis
- Acq Time Req
- Safety

**NO ACQUISITION SEARCH METHOD**
- On-Board
- LWIR
- Microwave
- Grind Upgrade
- Optical
- Ston/Gils
- Spads/SAS

Loss of Lock-On

Reacq Methods Safety Requirements for No Acq. or Loss of Lock-On

**AIM-POINT REGS (INCLUD SAFETY)**
- Transfer Opt
  - Time
  - Propellant
  - Power
- Sensor Data Processing
- TV Remote Backup Considerations
  - Acq of Docking Retro Reflector
    - No Acq
    - Circum-Nav
    - Grid Asst
    - Acq Aids
- Transfer Optimization
  - Time
  - Propellant
  - Power

**STANDOFF POINT REGS**
- BURNS NEAR PAYLOAD
- EVALUATION
- Docking Errors
- Propellant SLOSH
- Abort Considerations
  - TV Remote Backup Consideration
  - Firm Considerations
    - Non-Nominal Payloads
      - Slowly Rotating
      - Damaged Payload
      - Propellant SLOSH Effects
  - Effects of Burn, i.e., Impingement
  - Sensor FOV Considerations
    - Sensor vs Reflector Placement
    - Propellant SLOSH Effects
  - TV Remote Backup Requirements
  - Abort Regrets (Includ Tug Failure)
FIG. 4-1 AVIONICS CONFIGURATION FOR RENDEZEVOUS AND DOCKING

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Section 5
DOCKING SENSOR REQUIREMENTS

5.1 INTRODUCTION

The Docking Sensor is the key piece of hardware for Autonomous Docking. The following requirements can be modified by trade-offs with other parameters both internal and external to the sensor. The final requirements should be a judicious compromise of all the requirements in order to optimize the total system.

5.2 ACQUISITION RANGE

The sensor shall have a 0.99 probability of acquiring a passive cooperative payload at a minimum range of (77.6 nm) or 143.72 km.

This range is based on the 3-sigma guidance accuracy and payload uncertainty as specified in Section 2. It assumes that the tug reorients prior to entering within the acquisition range of the sensor and the boresight of the sensor is pointed at the center of the search volume.

The nominal aim point for the rendezvous burn is computed by:

\[
\text{Aim Point (AF), (nm)/RM} = \left\{ \frac{\text{PU}^2 \cdot \text{GAP}_1^2}{\text{GAV}_1} \left[ \frac{\text{GAV}_1 (\text{SFT} + \text{DTI})}{6076} \right]^2 + \text{DA}^2 \right\}^{1/2}
\]

where:

- PU = 3 Payload position uncertainty, (nm)km
- GAP_1 = 3 Guidance position accuracy, (nm)km
- GAV_1 = 3 Guidance velocity accuracy of GAP, (ft/sec); 6076 km/sec
- SFT = Search Frame Time, sec
- DTI = Data Taking Interval, sec
- DA = Deacceleration Time, sec
This Aim Point will insure that there cannot be an impact with the payload no matter what the guidance dispersions are perpendicular to GAP₁ or with 3-sigma dispersions in payload position, GAP or GAV. The relative orbital motion has been neglected as its effect is second order.

The time needed to cancel the guidance velocity error to avert impact is:

\[
\text{Deacceleration Time (DA, SEC) = } \frac{(GAV)^2 M}{2T (6076)}
\]

where:

\[M = \text{mass of vehicle (slugs), kg}\]
\[T = \text{Thrust (1bₚ), n}\]

The acquisition range (ACQ) then is:

\[
ACQ \ (\text{nm, km}) = \left[ AP^2 + (GAP_2)^2 + (GAP_3)^2 \right]^{1/2}
\]

Thus for 100 sensor measurements, a search frame time of 1.41 sec., a vehicle mass of 14810.5 kg (1014.84 slugs) and a retro thrust of 44.8 n (100 lb) along an axis which has the maximum GAP, the acquisition range is 143.72 km (77.6 nm).

5.3 FIELD OF VIEW

Fig. 5-1 is a graph of the sensor's field of view requirement, with and without a guidance update after the rendezvous burn. The closest range after rendezvous is 250.2 m (821 ft.) or .25 km (.135 nm). This distance and the payload uncertainty in the relative position of the tug are the drivers for FOV requirements. If it is desired to guarantee that the payload is within the FOV then the FOV required is \(\pm 1.57 \times \pm 1.57 \ \text{rad} (\pm 90^\circ \times \pm 90^\circ)\). With no guidance update the FOV requirements decrease slowly as the initial range increases. The FOV requirements with a guidance update decreases much more rapidly. A 99% probability that the payload will be within the FOV requires \(\pm .96 \times \pm .96 \ \text{rad} (\pm 55^\circ \times 55^\circ)\) (assuming zero dispersions perpendicular to
the payload - Aim Point axis).

With horizon sensors or star trackers to provide the initial altitude reference and a requirement of 0.1% torquing accuracy for the maneuver, altitude errors will not appreciably increase the FOV requirements.

5.4 SEARCH FRAME TIME (SFT)

The primary requirement for SFT is to achieve lock-on before the payload can drift out of the field of view. If we RSS the guidance velocity error perpendicular to the line of sight again neglecting orbital dynamics:

\[ v_{rel} = 6.04 \text{ m/sec (19.8 ft/sec)} \]

Requiring the addition to the FOV at closest range be no more than 10% due to SFT so as to be negligible when RSS with the sensor then:

\[ SFT = \frac{\text{initial range} \times \tan(\text{FOV})}{v_{rel}} \]

Thus for \( \pm 0.96 \times \pm 0.96 \text{ rad (} \pm 55^0 \times 55^0 \text{) FOV} \):

\[ SFT = \frac{(821) \times (0.19438)}{19.8} = 8.06 \text{ sec} \]

5.5 RANGE, ELEVATION AND AZIMUTH ACCURACY

Preliminary simulations show that the following 3-sigma accuracies would allow successful latch-up.

Range: 0.1% of range
Angle: 0.0008725 rad (0.05°)

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5.6 BIAS AND RESOLUTION

Bias is the most difficult sensor error to accommodate. Many sensor biases can be measured optically and by other methods. The known systematic error should be compensated for. Preliminary simulations allow the following resolution and 3-sigma biases:

<table>
<thead>
<tr>
<th>Resolution:</th>
<th>Range</th>
<th>.09 m, (0.3 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Angle</td>
<td>.0436 m rad (0.0025 deg.)</td>
</tr>
</tbody>
</table>

Bias:

<table>
<thead>
<tr>
<th>Range</th>
<th>.0046 m (0.015 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>.0034 rad (0.0002 deg.)</td>
</tr>
</tbody>
</table>

5.7 ACQUISITION AND TRACKING RATES

The following minimum rates are suggested:

Acquisition: 0.0279 rad/sec (1.66/sec)

Tracking: 0.0506 rad/sec (2.99/sec.)

Fig. 5-2 is the encounter relationships.

5.8 LOSS OF LOCK-ON

If for any reason the sensor loses lock-on for three consecutive measurements, the sensor should start an expanding squares or spiral search about the last known position. If the payload is not reacquired within one second after the loss of the payload then a loss of payload signal should be provided to abort the docking during a critical phase and the sensor should then initiate the full FOV raster scan.

5.9 DISCRIMINATION

The sensor should be able to discriminate against objects other than the payload in the FOV. These would be primarily the star background. Space debris could be eliminated to some extent by range gating and relative velocity.
discrimination. There should be an indicator if there is more than one ob-
ject in the FOV after discrimination.

The sensor should be able to operate if the sun, moon, or earth limits are
more than 0.08725 rad (5°) from the FOV. There cannot be any damage to
the sensor if the sun, moon, or earth appear in the FOV and the sensor
should recover normal operation within 10 sec.

5.10 DATA FREQUENCY RATE

The data frequency rate is usually driven by other sensor requirements such
as the pulse repetition frequency, data processing method, acquisition and
tracking rate requirements, etc. Preliminary simulation shows that a mini-
mum of 16 range, azimuth, and elevation measurements per second is adequate.
CLOSEST INITIAL APPROACH .25 km (.135 N-MI)

FIG. 5-1 SENSOR FIELD OF VIEW REQUIREMENTS

5-6

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ENCOUNTER GEOMETRY RELATIONSHIPS

\[
\frac{\dot{\theta}}{V_{\text{Ti}}/r_{\text{MIN}}} \quad \frac{\dot{r}}{V_{\text{Ti}}} \\
\frac{r/r_{\text{MIN}}}{10}
\]

\(\theta\) in degrees
\(100^\circ\)

\(r_{\text{MIN}} = \text{Range at closest approach}\)

\(t\)

Fig. 5-2 Encounter Relationships
Section 6
DOCKING MECHANISM DESIGN

6.1 INTRODUCTION

To assess the influence of the docking mechanism design on the type and accuracy of the data required, the description and mode of operation of existing and projected docking mechanisms were retrieved from the literature survey generated earlier. Of the list of docking systems described in Ref. 17, only the Gemini (Fig. 6-1), the Apollo (Fig. 6-2) and the Menasco (Fig. 6-3) systems were retained for further evaluation. To these were added the androgynous international docking system (Fig. 6-4) developed for the Apollo-Soyuz docking experiment and the "Square Frame" concept (Fig. 6-5) projected for the Space Tug. Description of these more recent concepts can be found in Ref. 20.

The requirements for an automatic docking system are formulated in Ref. 20 also. They can be expressed as follows:

The docking system shall be:

1. Comprised of mechanically mated, automatically operated parts which self-align and self-actuate on contact to provide a load carrying mechanical connection between chaser and target vehicles.

2. Simple.

3. Reliable.

4. Low in weight.

5. Capable of independent release on command using power furnished by the chaser vehicle.
Fig. 6-1 Gemini Docking System

Fig. 6-2 Apollo Docking System
Fig. 6-3 Menasco Docking System

Fig. 6-4 International Docking System
Fig. 6-5 Square Frame Docking System
6. Restored to a ready condition, on both the target and the chaser vehicles, prior to undocking or separation.

7. Fitted with components so as to give a clear field of view to optical, radar, or laser sensors on the chaser vehicle and reflectors on the target vehicle during rendezvous and initial capture.

8. Equipped, of possible, with three latching points for the docking system design. (More than three is unnecessarily redundant - less than three is not structurally stable or efficient.)

9. Equipped with latch and contact points located near the vehicle mold line to minimize loads due to bending.

10. Equipped with automatic latching devices designed to carry loads during boost from earth to earth orbit, as well as loads during inter-orbit transfer operations.

11. Designed with structure to absorb impact loads without shock absorbers or load attenuators, if possible.

It is believed that the following requirements should be added:

12. Design system to perform roll indexing and establish a hard line electrical connection.

Such a capability will enable the chaser vehicle to activate devices aboard a disabled target vehicle. It is envisioned that protruding components such as antennas and solar panels will have to be retracted or jettisoned before any retrieval mission can be accomplished. A service mission would also require a precise roll alignment of the spacecraft.

In order to make a first attempt at the evaluation of the five docking concepts mentioned, values ranging from 0 to 3 were attributed to each of the requirements.
Not enough information was gathered to evaluate the docking systems on requirements 4 and 11. It is believed that requirement 11 will make positive capture at first attempt harder to achieve and will bring a weight penalty to any concept designed without impact attenuators.

Table 6-1 shows the results of the preliminary evaluation of the five docking systems selected.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Gemini</th>
<th>Apollo</th>
<th>Menasco</th>
<th>International</th>
<th>Square Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
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<td>3</td>
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<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>26</strong></td>
<td><strong>22</strong></td>
<td><strong>23</strong></td>
<td><strong>27</strong></td>
<td><strong>25</strong></td>
</tr>
</tbody>
</table>

Rating based on evaluation of docking system capability to meet requirements listed.

- 3 = yes
- 2 = probably
- 1 = doubtful
- 0 = no

6.2 FIVE DOCKING CONCEPTS STUDIED

The following comments on each docking system may help in a further appraisal of the five concepts.
(1) **Gemini Concept**: In relation to the other systems, this concept is losing points on requirements 5 and 9.

The Gemini Agena Target Vehicle was supplying all the power required for the actuation of the docking mechanism. The docking approach maneuvers were performed by the chaser vehicle but all the docking active latching and mooring operations were performed by the target vehicle. If this concept is considered for automatic docking, the active mechanism, (in this case, the internal docking cone) should be installed on the chase vehicle and the passive external cone be part of the target vehicle. This new configuration would have the other advantage to provide more space inside the internal docking cone to install the optical, radar and laser sensors required for the automatic rendezvous and docking operations.

If such a modification of the Gemini docking concept proves feasible, then the rating to requirement 5, in Table 6-1 should be changed to 3, and the total becomes 29 instead of 26.

As far as requirement 9 is concerned, the docking latch receptacles are installed in the external docking cone which has a diameter of approximately 81.28 cm (32 in.). If the target vehicles are in a diameter range of 1.52 to 2.13 m (5 to 7 ft) and the center of gravity is located within the permissible space to prevent jackknifing of the spacecraft on impact, the existing Gemini hardware could probably be used. For vehicles having larger diameters and where their center of gravity are outside the permissible limits, it is conceivable that a larger diameter Gemini docking system could be designed to meet the conditions of requirement 9.

(2) **Apollo Concept**: The reason this concept was slightly derated on requirement 3, was that thrust has to be applied to the chaser vehicle following impact to achieve a successful capture. (Ref. 19)

The fact that the probe head and drogue capture receptacle are on the center line of the respective spacecraft, installation of the rendezvous and docking
sensors is made more difficult and their field of view is restricted by the extended probe mechanism of this concept. These are the reasons for a low rating on requirement 7.

A low rating on requirement 9, is due to the fact that the first impact load is reacted by the probe head which is on the center line of the chaser vehicle, and thus has a tendency to cause the vehicles to jackknife. This docking mechanism must resist a greater bending moment to align the vehicles after impact and capture.

No means to correct an angular misalignment in the roll axis during the docking or mooring operations resulted in a low rating for requirement 12.

(3) Menasco Concept: This concept, with its latch hooks running up and down the radial movable arms, is not simple. Although tests have been conducted successfully on a full-scale prototype mechanism (Ref. 17), it seems complicated and not as reliable as the other selected systems. It does not show any provision to align the two vehicles in the roll axis.

The above remarks are the reasons for low ratings on conditions 2, 3, and 12.

(4) International Concept: It is believed that this system has not been flight tested yet and this is the reason it was slightly derated under the requirements 2 and 3. Although it provides an angular alignment in the roll axis, it does not seem to be as accurate as in the Gemini system.

(5) Square Frame Concept: Although not much information has been found in the literature about this concept, an attempt was made at rating it against the other four better known systems. Due to the fact that no known models of this concept have been built or tested, a low rating on reliability was given.
Inherently this system has to have a minimum of four latches due to its design. For this reason, a slightly lower rating was given for requirement 8. A triangular frame may have some structural advantages over a square one, but it may not accommodate as large an angular misalignment in the roll axis. It is not in the scope of this study to investigate such a change in design. Lack of information about the structural integrity of the latching components was the reason for a lower rating on requirement 10.

A lower rating on requirement 12 has been given because it is believed that this concept does not provide a roll indexing as accurate as in the Gemini system.

Our evaluation study would not be complete without a comparison of the capabilities of each docking system. To date only the specifications of the Gemini, Apollo and the projected Space Tug could be found. The "Square Frame" concept is believed to be designed to the Space Tug docking specifications. (Ref. 22). A comparison of these specifications is shown in Table 6-2.

### Table 6-2

<table>
<thead>
<tr>
<th>Docking Accuracy Structural Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Centerline Miss Distance (ft)</td>
</tr>
<tr>
<td>m</td>
</tr>
<tr>
<td>Miss Angle (deg)</td>
</tr>
<tr>
<td>rad</td>
</tr>
<tr>
<td>Longitudinal Velocity (ft/sec)</td>
</tr>
<tr>
<td>m/sec</td>
</tr>
<tr>
<td>Lateral Velocity (ft/sec)</td>
</tr>
<tr>
<td>m/sec</td>
</tr>
<tr>
<td>Angular Velocity in Pitch, (deg/sec)</td>
</tr>
<tr>
<td>rad/sec</td>
</tr>
<tr>
<td>Yaw,</td>
</tr>
<tr>
<td>rad/sec</td>
</tr>
<tr>
<td>Roll,</td>
</tr>
<tr>
<td>rad/sec</td>
</tr>
<tr>
<td>Combined</td>
</tr>
</tbody>
</table>

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6.2 INFLUENCE OF DOCKING MECHANISM DESIGN

Analysis of the specifications in Table 6-2 shows that any of the concepts would be satisfactory for the Space Tug, although Table 6-1 rates the International system the best.

The specification that influences the Space Tug the greatest is the centerline miss distance. Figure 6-6 shows the total impulse required, for an abort, with a 15.24 cm (6 in) and 30.48 cm (12 in) specification for the centerline miss distance. The total impulse required drops from 9786 N-sec (2200 LBf-sec) for 15.24 cm to 4092 N-sec (920 LBf-sec) for 30.48 cm allowance.

It can be concluded that to minimize the influence on the Tug the centerline miss distance should be made as large as practicable consistent with the docking mechanism optimization.
Figure 6-6
ABORT BURN IMPULSE VS. DOCKING MECHANISM ERROR ALLOWANCE

6-11

LOCKHEED MISSILES & SPACE COMPANY
Section 7
ABORT

7.1 INTRODUCTION

This study has shown that a severe constraint on the abort process is imposed by thruster impingement on the payload. Docking mechanism requirements and control of the position and velocity errors normal to the docking axis are the other major drivers.

7.2 AUXILIARY PROPULSION SYSTEM (APS) IMPINGEMENT EFFECTS ON DOCKING

An impingement study of the APS thrusters was made applicable to any payload shape. Figs. 7-1 through 7-8 are for one forward firing thruster. The effect of two thrusters firing, which will be the usual case, can be easily derived as the impingement is symmetrical.

Fig. 7-9 through 7-16 are for thruster firing normal to the Tug X-axis. The impingement forces and torques are a function of the distance the payload is from Tug stations 457 and the payload are exposed to the plumes.

The forces and torques for any payload shape may be estimated by using the overlay included with this report over a suitable scaled payload outboard profile. The average segment surface pressure may be graphically integrated to find the force on the payload. The center of pressure is at centroid of the segment yielding the torque. Note that the pressures are symmetrical about the vertical axis and that the force and torque from the complementary thruster must be included.

It is obvious from Fig. 7-8 that even 1524 cm (600 in) from the payload the X-force for two thrusters tending to push a 1270 cm (500 in) radius payload
away from the Tug is 171.3 newton (38.5 lbf) which is highly undesirable.

Fig. 7-17 shows the total force and Torque on the payload as a function of the x-displacement for a 1270 cm (500 in) radius and a 508 cm (200 in) radius payload. Note that the x-force peaks when the tug is 215.9 cm (85 in) from the payload while the torque peaks at 609.6 cm (240 in). While the 508 cm radius payload is subjected to much less force, the force is still 69% of the 1270 cm payload at zero displacement. The & torque would cancel if the payload were perfectly symmetrical, the thrusts equal, and the Tug position exactly on the axis of the payload, an unlikely situation.

For the same conditions as above, but firing thrusters normal to the X-axis the X-force is only 0.417 newtons (0.094 lbf) a factor of 410 times less than for forward firing thrusters while the torque is 203 times less.

Figs. 7-18 and 7-19 show the torques and forces for a 1270 cm and 508 cm radius payloads. Note from Fig. 7-19 that there are no effects of impingement beyond 762 cm (300 in).

This suggests that the abort maneuver should be made by firing the thrusters normal to Tug X-axis.

The APS impingement effects on the Tug itself were not studied, however it can be concluded that the fore-aft thruster should be canted upward to reduce the impingement torques on the Tug itself and reduce the high stagnation temperatures on the vehicle.

7.2 ABORT

7.2.1 Introduction

Abort strategy and implementation are very important. An abort, which can occur for many reasons, has a severe impact on the mission because of time and total impulse requirements. The fundamental tenets for abort would be:
(1) Tug and payload safety must not be compromised.
(2) The payload attitude must not be destabilized.
(3) The additional total impulse required must be minimized.
(4) The time required to redock must also be minimized.

The following analysis assumes:

(1) $-Z$ axis thrusters for the abort burn, that is, the tug clears the underside of the payload.
(2) The payload docking mechanism is in the center of the payload and requires 508 cm clearance below the docking axis.
(3) The payload cannot control more than 13.6 cm-n (1.2 in-lbf) torque.
(4) The Tug's position and velocity errors normal to the docking axis are independent and normal, assuming 10.8 cm and .004 m/sec (3-sigma).
(5) The Tug is as defined in Section 2.
(6) The coordinates for the abort problems are shown in Fig. 7-20.
(7) The docking axis miss distance .152 m (.5 ft) and docking velocity = .152 m/sec (.5 ft/sec).
(8) Minimum allowable range to payload 1.829 m (6 ft).

In general, the smaller the time allotted for a maneuver or phase the greater the total impulse consumed will be.

7.2.2 Selection of the Stand Off Point (SOP) and Docking Velocity (VDOCK)

The first step is to determine the minimum abort range required. Given the docking mechanism normal (to the docking axis) error and the normal velocity...
(3-sigma) allocated at the SOP, Fig. 7-21 can be used to determine the minimum abort range. As an example, using the parameters in Section 2 and Para. 7.2.1, the minimum abort range is 4.176 m (13.7 ft).

The minimum abort distance should be selected to minimize the docking velocity while not violating other constraints. Here the docking velocity .152 m/sec or (.5 ft/sec) has been selected.

The next step is to determine the abort burn time from Fig. 7-22. The illustration uses 508 cm as the required clearance below the docking mechanism axis. Thus, the abort burn time and total impulse can be extrapolated as 10.8 sec or 4804 N-sec (1080 lbf-sec).

The minimum range can be checked with Fig. 7-23. In this case, the 1.829 m (6 ft) is safe by .21 m (.7 ft).

The last check, payload torque, is made using Fig. 7-24. The graph is entered using the abort burn time. At the point this time intersects the docking velocity-minimum abort range curve a line is drawn horizontally to intersect the Y torque curve and the magnitude of the Y-torque is read from the abscissa. For the example it is 11.98 cm-n (1.06 in-lbf); less than the specification of 13.56 cm-n.

For this case the SOP chosen would be 4.176m and the docking velocity .152m/sec.

7.2.3 Abort Impulse Calculation

The total impulse required for abort that is implemented in LOC DO K is:

\[
I_T = 2I_{TA} + I_{TOD} + \text{MASS} \left( 2 \left( V_{RY} + V_{OD} \right) + V_{\text{Retro}} \right)
\]

\[
I_{TA} = 50 \left[ \frac{2 \text{ Ra}}{V_{\text{D OCK}}} - \sqrt{\left( \frac{2 \text{ Ra}}{V_{\text{D O CK}}} \right)^2 - \frac{8 (Y_c + 7.33)}}{a} \right]
\]
\[ V_{\text{Retro}} = \left( \frac{R_2\, \text{min} + 23.3 + P_w}{t_I} \right) \]  \hspace{1cm} (7.3)

\[ V_{R_y} = \frac{Y_c + Y_{\text{safety}}}{t_I} \]  \hspace{1cm} (7.4)

where:

\[ I_t \] = Total impulse required for abort and redocking

\[ R_a \] = Standoff point distance

\[ Y_c \] = Clearance required below docking mechanism axis

\[ Y_{\text{safety}} \] = Clearance below \( Y_c \) required for antenna, etc.

\[ a \] = Acceleration of Tug thrust/vehicle mass

\[ V_{\text{dock}} \] = Docking velocity

\[ R_{2\, \text{min}} \] = Distance from payload on the docking axis to start final docking approach

\[ t_I \] = time allocated to return to \( R_{2\, \text{min}} \) from below payload after abort

\[ P_w \] = Payload width

\[ V_{R_y} \] = Velocity along the Y-axis

\[ I_{\text{TOD}} \] = Total impulse required to reach the SOP from \( R_{2\, \text{min}} \)

\[ I_{\text{TA}} \] = Initial abort burn total impulse

7-5
Equation 7.1 accounts for all the total impulse needed to abort, return to a point on the docking axis for another final approach, and return to the SOP. It does not include the total impulse needed by the attitude control system.

To recognize the factors that contribute the greatest amount to the abort impulse required, the following typical values in addition to those specified previously are assumed:

- \( V_{OD} = 0.152 \text{ m/sec (}.5 \text{ ft/sec)} \)
- \( I_{TOD} = 66723.3 \text{ N-sec (15,000 lbf-sec) from LOCDOK simulation} \)
- \( P_w = 10.16 \text{ m (33.34 ft)} \)
- \( R_{2 \text{ min}} = 304.8 \text{ (1000 ft)} \)
- \( Y_{safety} = 22.63 \text{ m (74.25 ft)} \)
- \( t_I = 3600 \text{ sec} \)
- \( \text{MASS} = 14593.9 \text{ kg (1000 slugs)} \)

From Equation 7.1

\[
I_t = 2160 + 15000 + 1000 (2 (.0253 + .5) + .2935)
\]

\[
I_t = 2160 + 15000 + 1399.5
\]

\[
I_t = (18559.5 \text{ lbf-sec}) 82556.7 \text{ N-sec}
\]

7-6
It immediately becomes obvious that the most impulse is used by the redocking run down the docking axis. The abort impulse is next, with the impulse required to regain $R_{2\text{ min}}$ the least. Note, however, from Equation 7.3 that this impulse is inversely proportional to the time allotted in arriving at $R_{2\text{ min}}$ and potentially it could become very large if the time allotted is short.

7.2.4 Abort Time Calculation

The time required $t_A$ to redock the tug is:

$$t_A = t_C + t_{CB} + t_I + t_{VOD} + t_{OD}$$  \hspace{1cm} (7.5)

$$t_C = \frac{R_a}{V_{DOCK}}$$  \hspace{1cm} (7.6)

$$t_{CB} = \frac{P_w + 23.3 + \frac{V_{DOCK}^2 + V_{Retro}^2}{2a}}{V_{DOCK}}$$  \hspace{1cm} (7.7)

$$t_{VOD} = \frac{V_{OD}}{a}$$  \hspace{1cm} (7.8)

$$t_{OD} = \frac{R_{2\text{ min}}}{V_{OD}}$$  \hspace{1cm} (7.9)

where:

$$V_{OD} = \text{Velocity down the docking axis from } R_{2\text{ min}} \text{ to } R_a$$

From Equation 7.5:

$$t_A = 27.4 + 116.6 + 3600 + 5 + 2000$$

$$t_A = 5749 \text{ sec, 1.6 hrs}$$

7-7

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More than half the time required for redocking is used in re-establishing the Tug's position for a run down the docking axis.

While this time can be shortened, it would increase the total impulse needed for the abort.

The second largest increment is used for the run down the docking axis. The velocity VOD selected was 0.152 m/sec (0.5 ft/sec) to save the total impulse required to accelerate to VOD and deaccelerate to VDOCK.
AXIAL DISTANCE FROM NOZZLE EXIT PLANE (EXIT RADII)

AXIAL DISTANCE FROM NOZZLE EXIT PLANE (EXIT RADII)

\[
\frac{A_e}{A_t} = 75:1
\]

\[
\alpha = 1.29
\]

\[
\gamma = 2.714
\]

\[
F = (50 \text{ Lb}) \frac{2224 \text{ N}}{2224 \text{ N}}
\]

Fig. 7-1 Forward Thruster Impingement

7-y

LOCKHEED MISSILES & SPACE COMPANY. INC.
FIG. 7-3  FORWARD THRUSTER IMPINGEMENT 254 CM SEPARATION
FIG. 7-4  FORWARD THRUSTER IMPINGEMENT 508 CM SEPARATION
X MEASURED FROM FORWARD END OF TUG (STATION 457)

$M_y \text{ TOTAL FOR THIS SURFACE (ASSUMING C.M. ON X AXIS AT STATION X = 0)} = \frac{(4437 \text{ IN. LB})}{50114.9 \text{ CM-N}}$

( ) = AVERAGE SEGMENT SURFACE PRESSURE X $10^6$ (PSIA)

X-FORCE, TOTAL (LB) = (26.626)

N = 118.438

FIG. 7-5 FORWARD THRUSTER IMPINGEMENT 762 CM SEPARATION
FIG. 7-6 FORWARD THRUSTER IMPELLMENT 1016 CM SEPARATION
\[ X \text{ MEASURED FROM FORWARD END OF TUG (STATION 457)} \]

\[ M_\gamma \text{ TOTAL FOR THIS SURFACE (ASSUMING C.M. ON X AXIS AT STATION X = 0)} \]

\[ = \frac{(4111 \text{ IN. LB})}{46448.0} \text{ N} \]

\[ ( ) \text{ = AVERAGE SEGMENT SURFACE PRESSURE X 10 (PSIA)} \]

\[ X \text{-FORCE, TOTAL (LB)} = 20.988 \]

\[ N = 93.359 \]

**FIG. 7-7 FORWARD THRUSTER IMPINGEMENT 1270 CM SEPARATION**
$X_{\text{TOTAL}} = (3860 \text{ in. lb}) \times 43997.9 \text{ cm-N}$

$X_{\text{force, total}} (\text{lb}) = (19.258) \times 85,664$
I1

ENGINE CHARACTERISTICS

\[ \frac{A_e}{A_t} = 75:1 \quad \gamma = 2.714 \]

\[ \alpha = 1.29 \quad F = (50 \text{ Lb}) \quad 222.4 \text{ N} \]

\[ 1524 \quad 1270 \quad 1016 \quad 762 \quad 508 \quad 244 \text{ (IN.) CM} \]

AXIAL DISTANCE FROM NOZZLE EXIT PLANE (EXIT RADII)

RADIAL DISTANCE FROM NOZZLE (EXIT RADII)

PAYLOAD \( \xi \) - - - - - - - TUG \( \xi \)

\( x \rightarrow \)

\( - - - \quad 40 \quad 35 \quad 30 \quad M=25 \)

\( y \rightarrow \)

\( 200 \quad 100 \quad 0 \)

Fig. 7-7 Normal Thruster Impingement
X = MEASURED FROM FORWARD END OF TUG (STATION 457) = (0 IN.) 0 CM

M_x TOTAL FOR THIS SURFACE (ASSUMING C.M. ON X AXIS AT STATION X = 0) = (487.7 IN. LB) 3508.5 CM

( ) = AVERAGE SEGMENT SURFACE PRESSURE X 10^5 (PSIA)

X-FORCE, TOTAL (LB) = (1.4855) N = 6.608

FIG. 7-10 NORMAL THRUSTER IMPINGEMENT 0. CM SEPARATION
FIG. 7-12 NORMAL THRUSTER IMPINGEMENT 508 CM SEPARATION
FIG. 7-13 NORMAL THRUSTER IMPINGEMENT 762 CM SEPARATION
X MEASURED FROM FORWARD END OF TUG (STATION 457) = (400 IN.) 1016 CM

\( M_Y \) TOTAL FOR THIS SURFACE (ASSUMING C.M. ON X AXIS AT STATION X = 0) = (3.4 IN. Lb.) 38.4 CM-N

\( M_Z \) TOTAL FOR THIS SURFACE (ASSUMING C.M. ON X AXIS AT STATION X = 0) = (52.0 IN. Lb.) 587.3 CM-N

\( ( ) \) = AVERAGE SEGMENT SURFACE PRESSURE X 10^5 (PSIA)

X-FORCE, TOTAL (LB) = (.13766)

\( N_z = .612 \)

FIG. 7-14  NORMAL THRUSTER IMPINGEMENT 1016 CM SEPARATION
FIG. 7-15  NORMAL THRUSTER IMPINGEMENT 1270 CM SEPARATION
FIG. 7-16 NORMAL THRUSTER IMPINGEMENT 152X CM SEPARATION
FIG. 7-17 PAYLOAD TORQUE AND FORCE VS X-DISTANCE FORWARD THRUSTER

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FIG. 7-18 PAYLOAD TORQUE AND FORCE VS X-DISTANCE NORMAL THRUSTER

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FIG. 7-19 PAYLOAD TORQUE AND FORCE VS X-DISTANCE NORMAL THRUSTERS
Fig. 7-25  Abort Calculation Coordinates
FIG. 7-21 ERR0R NORMA7 TO DOCKING AXIS VS ABORT RANGE AND NORMAL VELOCITY

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FIG. 7-22  PAYLOAD CLEARANCE BEFORE DOCKING AXIS VS ABORT RANGE, DOCKING VELOCITY AND ABORT BURN TIME

7-30

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MIN RANGE VS ABORT BURN TIME

FIG. 7-23  MINIMUM BURN TIME VS ABORT BURN TIME

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7-31
Fig. 7-24 Y-DISTANCES AT CLOSEST APPROACH VS. ABORT RANGE
DOCKING VELOCITY AND ABORT BURN TIME VS Y-TORQUE
8.1 INTRODUCTION

LOCDOK is a digital simulation of a space vehicle docking with a payload. This simulation was abstracted and modified from a much larger simulation, AVION. In constructing the program certain features, not required by the study were not included but the interfaces to permit incorporation in the future were retained. Some of these features are rendezvous, circumnavigation of the payload, and maintenance of fixed position.

8.2 LOCDOK SIMULATION

The LOCDOK simulation is written in Fortran IV for the Univac 1108 computer. It requires 62,782 decimal words of core storage and is not segmented. The program is modularized, containing 81 subroutines. The simulation may be run in English or in the International System of Units.

The program input data is preset to that only variables that require change for a particular run need be inputed. The input is designed so that multiple cases may be run without resubmission on the job.

The program has a versatile SC4020 plot capability which has the following features: All plotting data can be stored on computer magnetic tape to allow replotting at a later date without re-running the entire simulation. In addition, there is the capability to perform mathematical manipulation of the variables. These variables may be added, subtracted, divided, or multiplied; and of course one of the variables may be a constant. The program automatically scales all variables so as to fill the entire plot. If there are several dependent variables, the program automatically scales them so that adequate resolution is obtained, and then annotates each variable with its title and the scale factor, see Figs. 8-1 to 8-4.
Fig. 8-5 through 8-21 are sample pages of the output. All variables are labeled in English together with the important Fortran names. Definitions of the output variables are self-evident as can be seen from the output. Figures 8-5 and 8-6 are sample page outputs in metric units for perfect attitude control. Figures 8-7 and 8-6 are similar except in English units. Figures 8-9 and 8-10 illustrate the difference in output from the runs with detailed attitude control. Additional LOCDOK details may be found in the User's Manual, LMSC/D424229, which is submitted as a separate volume with this report.

8.2 USER'S MANUAL

The User's Manual, LMSC/D424229, is published separate from this volume for ease of use. Once an operator becomes familiar with LOCDOK, all information necessary to run the program can be found in the User's Manual, although occasional reference to the Final Report may be required at first.

All the input variables required to run the program are in the Input Dictionary Section of the User's Manual. Preset data values, Fortran names of the input variables, definition of the variables, together with limitations and notes, are also in the Dictionary.
FIG. 8-1 COMPUTER PLOT - ATTITUDE CONTROL TOTAL IMPULSE

FIG. 8-2 COMPUTER PLOT - REORIENTATION OF TUG TO ACQUIRE PAYLOAD

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FIG. 8-3 COMPUTER PLOT - TUG ATTITUDE

FIG. 8-4 COMPUTER PLOT - APS TOTAL IMPULSE AND ENGINE NO.
### Docking Maneuver Data

**Space Tug Docking Study**

**Program Controls**
- Integration Step Size: 0.150000000
- Print Cycle: 200 Steps
- Max. Time: 0.170000000

**Metric units will be used in this run**

**Guidance Parameters**
- LOS Engine Control (FK):
  - PK: 100000000.0
  - PB: 0.0000000
- Standoff Range:
  - FB: 121920000.0
  - RB: 0.147960000

**Propulsion Parameters**
  - ISP: 0.444000000
  - ISP: 0.330000000
  - ISP: 0.230000000
  - Thrust: 0.667240000
  - Thrust: 0.667240000
  - Thrust: 0.667240000
- SPS Minimum Impulse Btu:
  - %: 111200650.0
- Percent Error in Delta V:
  - #: 0.0000000

**Perfect Attitude Control is Assumed (Instantaneous Response)**

---

**Fig. 8-5**
Computer Output - SI Units, Perfect Attitude Control - Input Variables
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<th>BANDWIDTH</th>
<th>RANGE RATE</th>
<th>SENSOR NOISE CONSTANTS</th>
<th>EL LOS RATE</th>
<th>EL LOS RATE</th>
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<table>
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<th>OTHER INPUT VALUES</th>
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<tr>
<td>TUG AUX. FUEL MASS</td>
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<tr>
<td>TIME BETWEEN DATA POINTS</td>
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<tr>
<td>NO. OF DATA POINTS</td>
</tr>
<tr>
<td>MAXIMUM TIME FOR TRANSFER TO ROCK AX12</td>
</tr>
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<td>MINIMUM TIME FOR TRANSFER TO ROCK AX12</td>
</tr>
<tr>
<td>ENS DISTANCE THRESHOLD</td>
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<table>
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<tr>
<th>DOCKING PARAMETERS</th>
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<tr>
<td>ORIENTATION OF PAYLOAD DOCKING AXIS (DIRECTION COSINES)</td>
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<tr>
<td>UNP 1 = .10000000*01</td>
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<tr>
<td>UNP 2 = 00000000</td>
</tr>
<tr>
<td>UNP 3 = .00000000</td>
</tr>
<tr>
<td>MINIMUM RANGE ALLOWED ON DOCKING AXIS IN PLANNING GROOVE TRANSFER TO DOCKING AXI</td>
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<tr>
<td>ABSOLUTE VALUE OF RANGE RATE DESIRED AT START OF DOCKING MANEUVER (V0)</td>
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<tr>
<td>RAGE AT WHICH RANGE RATE IS REDUCED TO FINAL DOCKING VELOCITY</td>
</tr>
<tr>
<td>VELOCITY PERMITTED AT FINAL VELOCITY</td>
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<tr>
<td>FIG. 8-5 (CON'T)</td>
</tr>
</tbody>
</table>
DOCKING MANEUVER BEGINS

TIME = +00000000
TIME MAX = +2000000000

RELATIVE COORDINATES OF TUG & PAYLOAD

CT = +3271712000
K = +3271712000
IT = +3271712000
CTidot = +3271712000
Kdot = +3271712000
ITdot = +3271712000

ORBIT ELEMENTS OF PAYLOAD SATELLITE

ECCENTRICITY 0.016455903
INCLINATION 0.02145788
CENT ANGLE 0.02858762
ARG OF PERI 0.05654972
RIGHT ARC 0.0000000
TIME 0.0000000

ORBIT ELEMENTS OF TUG

ECCENTRICITY 0.029408102
INCLINATION 0.020044798
CENT ANGLE 0.114018890
ARG OF PERI 0.130570762
RIGHT ARC 0.0000000
TIME 0.0000000

INERTIAL PARAMETERS:

TUG POSITION

XI = +4289712000
X2 = +4289712000

Y2 = +3293246784
Z2 = +3293246784

TUG VELOCITY

VTO = +1073425000
V= +100000000

PAYLOAD POSITION

XI = +4254715243
Y2 = +4254715243

Z2 = +4254715243

PAYLOAD VELOCITY

VTO = +1073425000
V'= +100000000

ACQUISITION RANGE (KM) = +1637152000 (METERS) = +1637152000
INITIAL RANGE (KM) = +1637152000 (METERS) = +1637152000
ACQUISITION RANGE EXCEEDS INITIAL RANGE

HORIZONTAL LIMIT ANGLES (RADIAN) LIMIT ANGLE (RADIAN) AND GYRATOR TIME (SEC) (RELATIVE TO GYROBASE FRAMES)

AZIM. = -1.157205001
ELEV. = +1.257365001
RANGE = +1.157205001
TIME = +000000

AZIM. = +1.157205001
ELEV. = +1.257365001
RANGE = +1.157205001
TIME = +000000

AZIM. = +1.157205001
ELEV. = +1.257365001
RANGE = +1.157205001
TIME = +000000

AZIM. = +1.157205001
ELEV. = +1.257365001
RANGE = +1.157205001
TIME = +000000

AZIM. = +1.157205001
ELEV. = +1.257365001
RANGE = +1.157205001
TIME = +000000

NEAREST APPROACH WILL OCCUR IN = +1982465000 SEC AND THE RANGE WILL BE = +1982465000 METERS

DATA TAKING RATE ALTERED TO = +45500000000 IC MACH INTEGRATION STEP SIZE = +45500000000 SEC TRACKING INTERVAL REB TO = +45500000000 SEC TRACKING INTERVAL WILL END WHEN TIME = +45500000000 SEC

HPG = +15500000000 HPGV = +15500000000 PPG = +15500000000 PPGV = +15500000000

TIME = +00000000
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD

IN-TRACK VELOCITY (XS) = +5217120000
IN-TRACK VELOCITY (XS) = +5217120000
RADIAL VELOCITY (YR) = +42449999999
CROSS-TRACK VELOCITY (ZS) = +5926400000
CROSS-TRACK VELOCITY (ZS) = +5926400000

FIG. 8-6 COMPUTER OUTPUT - SI UNITS, PERFECT ATTITUDE CONTROL - DATA
### Final Values Follow

**Current Position and Velocity Relative to the Payload**
- **In-Track Position (XS)** = -9,431,085
- **In-Track Velocity (VSX)** = -1.516,010
- **Radial Position (YS)** = 0.930,000
- **Radial Velocity (YSY)** = -1.516,010
- **Cross-Track Position (ZS)** = -2.380,000
- **Cross-Track Velocity (ZSY)** = -2.380,000

Results corresponding to start of data gathering interval time:

<table>
<thead>
<tr>
<th>Extracted Range Vector</th>
<th>Extracted Vel Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASAT</strong></td>
<td><strong>VSAT</strong></td>
</tr>
<tr>
<td><strong>In-Track</strong> = -9,431,085</td>
<td><strong>In-Track</strong> = -1.516,010</td>
</tr>
<tr>
<td><strong>Radial</strong> = 0.930,000</td>
<td><strong>Radial</strong> = -1.516,010</td>
</tr>
<tr>
<td><strong>Cross-Track</strong> = -2.380,000</td>
<td><strong>Cross-Track</strong> = -2.380,000</td>
</tr>
</tbody>
</table>

**Standard Deviations Associated with Extracted Data**

- **Position**
  - **IT** = 0.516,010
  - **CT** = 0.516,010

<table>
<thead>
<tr>
<th>Position Vel. to Payload</th>
<th>Velocity Vel. to Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASATVE</strong></td>
<td><strong>VSATVE</strong></td>
</tr>
<tr>
<td><strong>IT</strong> = -9,431,085</td>
<td><strong>VIT</strong> = -1.516,010</td>
</tr>
<tr>
<td><strong>RAD</strong> = 0.930,000</td>
<td><strong>VRAD</strong> = -1.516,010</td>
</tr>
<tr>
<td><strong>CT</strong> = -2.380,000</td>
<td><strong>VCT</strong> = -2.380,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Desired Final Range Vector</th>
<th>Desired Final Velocity Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASAT</strong></td>
<td><strong>VSAT</strong></td>
</tr>
<tr>
<td><strong>In-Track</strong> = -9,431,085</td>
<td><strong>In-Track</strong> = -1.516,010</td>
</tr>
<tr>
<td><strong>Radial</strong> = 0.930,000</td>
<td><strong>Radial</strong> = -1.516,010</td>
</tr>
<tr>
<td><strong>Cross-Track</strong> = -2.380,000</td>
<td><strong>Cross-Track</strong> = -2.380,000</td>
</tr>
</tbody>
</table>

- **Distance normal to docking axis** = 0.930,000
- **Maximum tolerable distance from docking axis for retro-reflector viewing** = 0.930,000
- **TUG is not within viewing limits of retro-reflector on payload docking axis**

**Preliminary Appraisal of Cross Transfer to Docking Axis**

- **Time to be spent in each tracking session, sec** = 2.907,000

<table>
<thead>
<tr>
<th>Position-Relative-To-Payload to be reached in this maneuver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RSTMOV(1)</strong> = -9,431,085</td>
</tr>
</tbody>
</table>

**Current knowledge of tug's position relative to the payload**
- **RTOCIV(1)** = 9,431,085
- **RTOCIV(2)** = 0.930,000
- **RTOCIV(3)** = 2.380,000
- **Range to payload** = 1,900,000
- **Range to be traversed** = 1,900,000
- **Maximum possible time at present rate** = 1.54,000

- **For a standard deviation in measured position** = 0.2920,000
- **And an acceptable standard deviation in computed velocity** = 0.304,000
- **The shortest tracking interval needed** = 0.54,000

- **Based on 100 data points, the corresponding closest spacing of measurements** = 0.54,000

To meet velocity accuracy requirements: I have raised data taking rate to 0.967,000

**Time to be spent in each tracking session, sec** = 0.967,000

---

**Fig. 8-6 (Cont')**
DATA TAKING RATE ALTERED TO .07490000+01 TO MATCH INTEGRATION STEP SIZE
TOTAL TRACKING INTERVAL REMAIN TO .94574485+03 SEC TRACKING INTERVAL WILL END WHEN TIME = .10493900+01 SEC

HPS = .15000000+00 HP6I = .97499999+01 HFD = .97499999+01

TIME = .44100000+02
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD:
IN-TRACK POSITION (IS) = .55799926+06 IN-TRACK VELOCITY (ISD) = .36006677+01
RADIAL POSITION (YS) = .55997616+04 RADIAL VELOCITY (YSD) = .66400822+01
CROSS-TRACK POSITION (ZS) = .56077554+05 CROSS-TRACK VELOCITY (ZSD) = .42006291+01

FINAL VALUES FOLLOW

TIME = .98599999+00
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD:
IN-TRACK POSITION (IS) = .52739944+06 IN-TRACK VELOCITY (ISD) = .31732921+01
RADIAL POSITION (YS) = .54295746+05 RADIAL VELOCITY (YSD) = .38496661+01
CROSS-TRACK POSITION (ZS) = .54890609+05 CROSS-TRACK VELOCITY (ZSD) = .44649294+01

RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL TIME = .44009999+02
EXTRACTED RANGE VECTOR

EXTRACTED REL VEL VECTOR

<table>
<thead>
<tr>
<th>ASIATV</th>
<th>IN-TRACK</th>
<th>RADIAL</th>
<th>CROSS-TRACK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.55399261+06</td>
<td>.55079826+06</td>
<td>.54907059+06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>USATV</th>
<th>IN-TRACK</th>
<th>RADIAL</th>
<th>CROSS-TRACK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.36306524+01</td>
<td>.36480221+01</td>
<td>.42889143+01</td>
</tr>
</tbody>
</table>

STANDARD DEVIATIONS ASSOCIATED WITH EXTRACTED DATA

<table>
<thead>
<tr>
<th>POSITION</th>
<th>IT</th>
<th>RAD</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.11240177+02</td>
<td>.10856908+02</td>
<td>.11239901+02</td>
</tr>
</tbody>
</table>

END OF PRELIMINARY APPRAISAL

FIG. 8-6 (CON'T)
START OF GROSS TRANSFER

ACTUAL DURATION OF BURN OR TRACKING INTERVAL (SEC) = .958/15340/01

POSITION REL TO PAYLOAD
R5000 MV

IT = -1.527079405
RAD = -1.584969405
CT = -1.54995105405

VELOCITY REL TO PAYLOAD
V5000 MV

VIT = 1.3123769401
VRAD = 1.450111672401
VC = 1.42809349401

GROSS CORRECTION COMPUTATIONS

RANGE VECo AT BURN
R5000 MV

IN TRACK = -1.527079405
RADIAL = -1.584969405
CROSS TRACK = -1.54995105405

VECo AT BURN
V5000 MV

IN TRACK = 1.3123769401
RADIAL = 1.450111672401
CROSS TRACK = 1.42809349401

INITIAL GUIDANCE COMPUTATIONS TO START TRANSFER

DISTANCE TO BE TRAVERSED, METERS = .933610902405

PRESENT SPEED TOWARD FINAL OBJECTIVE = .70164902405 (PARALLEL TO RANGE VECTOR)

MISS DISTANCE ACCEPTABLE

PRESENT SPEED TOWARD FINAL OBJECTIVE = .70164902405 (PARALLEL TO RANGE VECTOR)

CURRENT VELOCITY COMPONENT IN THE ETA DIRECTION = .6641048400

TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION = .68363791400

JUST TO CANCEL CURRENT NORMAL VELOCITIES WILL REQUIRE = .24895888742 SECONDS

DESIRED VELOCITY COMPONENT IN THE ZETA DIRECTION = .12690103401

EXPECTED DURATION OF TRANSFER USING EXISTING RANGE RATE IS LESS THAN MAXIMUM ALLOWED

FINAL CALCULATIONS

PRESENT SPEED TOWARD FINAL OBJECTIVE = .70164902405 (PARALLEL TO RANGE VECTOR)

CURRENT VELOCITY COMPONENT IN THE ETA DIRECTION = .6641048400

TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION = .68363791400

JUST TO CANCEL CURRENT NORMAL VELOCITIES WILL REQUIRE = .24895888742 SECONDS

DESIRED VELOCITY COMPONENT IN THE ETA DIRECTION = .12690103401

TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION = .12690103401

JUST TO DEVELOP DESIRED NORMAL VELOCITIES WILL REQUIRE = .9229826402 SECONDS

DURATION OF NOMINAL FINAL BURN, SEC = .1174937403 DURATION OF TRACKING BEFORE FINAL BURN, SEC = .958/15340/01

FIG. 8-6 (CON'T)
TABLE 1

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>BURN VELOCITY VECTOR</td>
<td>DELTA V CT = 5.4572094640</td>
</tr>
<tr>
<td>DELTA V NR</td>
<td>DELTA V NR = 5.4572094640</td>
</tr>
<tr>
<td>DELTA V LR</td>
<td>DELTA V LR = 5.4572094640</td>
</tr>
<tr>
<td>COMPONENT OF BURN RELATIVE TO BODY AXES</td>
<td>X = 5.4572094640 Y = 5.4572094640 Z = 5.4572094640</td>
</tr>
<tr>
<td>DATA TAKING RATE ALTERED TO .017MS9.001 TO MATCH INTEGRATION STEP SIZE</td>
<td>DURATION OF VELOCITY COMPONENT BURNS (SEC) X = .117MS9.001 Y = .5372094640 Z = .2266449494</td>
</tr>
<tr>
<td>LONGEST BURN TIME ON ONE ENGINE IN THIS BURN-SET = .2266449494 SEC</td>
<td>SHORTEST BURN TIME ON ONE ENGINE IN THIS BURN-SET = .117MS9.001 SEC</td>
</tr>
<tr>
<td>THIS BURN WILL END WHEN TIME IS APPROXIMATELY = 1.18E-09</td>
<td></td>
</tr>
<tr>
<td>DATA TAKING RATE ALTERED TO .017MS9.001 TO MATCH INTEGRATION STEP SIZE</td>
<td>DURATION OF X-AXIS BURN IS LESS THAN INTEGRATION STEP SIZE AND WILL BE NEGLECTED</td>
</tr>
</tbody>
</table>

SIMULATION OF INTERCEPTOR BURN BY NUMERICAL INTEGRATION OF THRUST

| HPG | .100000000000 |
| HP81 | .100000000000 |
| HPFD | .9749999999 |

TIME = 2.89999999999

CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD

| IN-TRACK POSITION (XZ) | -5.3233053405 |
| IN-TRACK VELOCITY (XZ) | -3.0679999944 |
| RADIAL POSITION (Y)   | -3.5208348305 |
| RADIAL VELOCITY (Y)   | 3.9441901401 |
| CROSS-TRACK POSITION (Z) | -5.4444448406 |
| CROSS-TRACK VELOCITY (Z) | 3.6744444401 |

FIG. 8-6 (CON'T)
*** DOCKING MANEUVER DATA ***

SPACE TUG DOCKING STUDY

PROGRAM CONTROLS
INTEGRATION STEP SIZE = 0.1700000000
PRINT CYCLE 4000 STEPS
MAX. TIME  = 0.1700000000

ENGLISH UNITS WILL BE USED IN THIS RUN

GUIDANCE PARAMETERS

LOS ENGINE CONTROL (FK)  STANDOFF RANGE
FR  0.00000000  0.00000000  0.17000000

PROPULSION PARAMETERS

MAIN ENG. ISP  AXIAL ENG. ISP  LATERAL ENG. ISP  MAIN ENG. THRUST  AXIAL ENG. THRUST  LATERAL ENG. THRUST
0.9440000000  0.2400000001  0.1000000000  0.1900000000  0.1000000000  0.1000000000
SPS MINIMUM IMPULSE MIT = 0.2400000001
PERCENT ERROR IN DELTA VE = 0.0000000

PERFECT ATTITUDE CONTROL IS ASSUMED (INSTANTANEOUS RESPONSE)

FIG. 8-7  COMPUTER OUTPUT - ENGLISH UNITS PERFECT ATTITUDE CONTROL INPUT VARIABLES
<table>
<thead>
<tr>
<th>BANDWIDTH</th>
<th>RANGE</th>
<th>RANGE RATE</th>
<th>SENSOR NOISE CONSTANTS</th>
<th>AZ LOS RATE</th>
<th>EL LOS RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
</tr>
<tr>
<td>MULTIPLIER 1000000001</td>
<td>1000000001</td>
<td>1000000001</td>
<td>1000000001</td>
<td>1000000001</td>
<td>1000000001</td>
</tr>
<tr>
<td>LOWER RANGE LIMIT 1000000001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
</tr>
<tr>
<td>UPPER RANGE LIMIT .4719066406</td>
<td>.4719066406</td>
<td>.4719066406</td>
<td>.4719066406</td>
<td>.4719066406</td>
<td>.4719066406</td>
</tr>
<tr>
<td>STANDARD DEVIATION .1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
</tr>
</tbody>
</table>

**NOISE CONSTANTS CONTINUED**

<table>
<thead>
<tr>
<th>AZIMUTH (LOS)</th>
<th>ELEVATION (LOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1141590001</td>
<td>.1141590001</td>
</tr>
<tr>
<td>MULTIPLIER (ELEV) 1000000001</td>
<td>1000000001</td>
</tr>
<tr>
<td>LOWER RANGE (E) .1141590001</td>
<td>.1141590001</td>
</tr>
<tr>
<td>UPPER RANGE (H) .4719066406</td>
<td>.4719066406</td>
</tr>
<tr>
<td>STANDARD DEVIATIONS (SIGMA) .1141590001</td>
<td>.1141590001</td>
</tr>
</tbody>
</table>

**SENSOR RESOLUTION AND BIAS INPUTS**

<table>
<thead>
<tr>
<th>RANGE</th>
<th>RANGE RATE</th>
<th>RAD/SEC</th>
<th>DEG/SEC</th>
<th>RANGE RATE BIAS</th>
<th>DEG/SEC</th>
<th>RANGE</th>
<th>RANGE RATE</th>
<th>RAD/SEC</th>
<th>DEG/SEC</th>
<th>RANGE RATE BIAS</th>
<th>DEG/SEC</th>
<th>AZ</th>
<th>EL</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
<td>.1141590001</td>
</tr>
</tbody>
</table>

**OTHER INPUT VALUES**

- TUG Dry Mass = .1141590001
- TUG Main Eng Fuel Mass = .1141590001
- TUG Total Mass = .1141590001
- Time Between Data Points = 100
- No. of Data Points in Data Take = 100
- Minimum Time for Transfer to Dock Axis = 1000000001
- Maximum Time for Transfer to Dock Axis = 1000000001
- Sensor FOV Half-Angles = 50
- Percent Error in Delta V0 = .1141590001
- Miss Distance Threshold = .1141590001
- Sensor Acquisition Range (H/M) = .1141590001

**DOCKING PARAMETERS**

- Orientation of Payload Docking Axis (Direction Cosines) UNX = - .1141590001 UNY = .1141590001 UNZ = .1141590001
- Minimum Range Allowed on Docking Axis in Planning Gross Transfer to Docking Axis = .1141590001
- Absolute Value of Range Rate Desired at Start of Docking Maneuver (V0) FTSEC = .1141590001
- Range at Which Range Rate is Reduced to Final Docking Velocity (Vstop) = .1141590001
- Defined Final Impact Speed (Vnorm) = .1141590001
- Velocity Permitted at RSUR (Tol Vel) = .1141590001

**FIG. 8-7 (CON'T)**
LOCKHEED MISSILES & SPACE COMPANY

FIG. 8-8 COMPUTER OUTPUT - ENGLISH UNITS, PERFECT ATTITUDE CONTROL DATA
FINAL VALUES FOLLOW

CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD:
IN-TRACK POSITION (X) = 3433576.68 + 35 IN-TRACK VELOCITY (X,0) = .544848136 + 01
RADIAL POSITION (Y) = 16521228.83 RADIAL VELOCITY (Y,0) = .6134665195
CROSS-TRACK POSITION (Z) = 19077740 + 83 CROSS-TRACK VELOCITY (Z,0) = .376522816 + 03

RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL T = 0.00000000

EXTRACTED RANGE VECTOR

IN-TRACK = 3433576.68 + 35
RADIAL = 16521228.83
CROSS-TRACK = 19077740 + 83

STANDARD DEVIATIONS ASSOCIATED WITH EXTRACTED DATA

POSITION

CT = .4462749 + 02 .3572157 + 02 .3834637 + 01

VELOCITY REL TO PAYLOAD

IT = .92363132 + 02 VIT = .50232255 + 01
RAD = .16727280 + 02 VRAD = .6237166 + 01
CT = .164793748 + 02 VCT = .37659877 + 02

DESIRED FINAL RANGE VECTOR

IN-TRACK = 1288888.30 + 83
RADIAL = 34868888
CROSS-TRACK = 54838888

DESIRED FINAL VELOCITY VECTOR

VFV

IN-TRACK = 28000000 + 01 RADIAL = 34868888 CROSS-TRACK = 54838888

DISTANCE NORMAL TO DOCKING AXIS = .11949282 + 03
MAXIMUM TOLERABLE DISTANCE FROM DOCKING AXIS FOR RETRO-REFLECTOR VIEWING = .2276922 + 03
TUG IS WITHIN RETRO-REFLECTOR VIEWING LIMITS

REMAINING TOTAL MASS = .1867968 + 04 REMAINING MAIN ENG PROP MASS = .3639799 + 03 REMAINING APS PROP MASS = .2123000 + 02

TRANSFER TO DOCKING AXIS COMPLETED

FIG. 8-8 (CON'T)
DESIRED FINAL RANGE VECTOR

IN TRACK = +1378888+00
RADIAL = +888888+00
CROSS TRACK = +888888+00

DESIRED FINAL VELOCITY VECTOR

IN TRACK = 000000+00
RADIAL = 000000+00
CROSS TRACK = 000000+00

WIDEGUARD TRACKING COMPUTATIONS

POSITION REL TO PAYLOAD

ITX = +9220222222
RAD = +1675923248
CTX = +18097827485

VELOCITY REL TO PAYLOAD

VITX = +92079190621
VRAD = +92079190621
VCTX = +92079190621

STANDARD DEVIATIONS OF NOISE

FIRST COMPONENT

BEARING = +13589237481
ELEVATION = +8585987493+00
AZIMUTH = +8593422646+00

SECOND COMPONENT

ROOT-SUM-SQUARE = +97588927481
TOTAL TRACKING INTERVAL REMAINING = +1406366+00 SEC
TRACKING INTERVAL WILL END WHEN TIME = +298499999+00 SEC

HPR = +150686888+00 HPG = +150686888+00 HPD = +150686888+00

TIME = +147866666+00

CURRENT POSITION AND VELOCITY, RELATIVE TO THE PAYLOAD

IN-TRACK POSITION (X) = +38268158+01
IN-TRACK VELOCITY (XRD) = +38268158+01
RADIAL POSITION (Y) = +1653423248
RADIAL VELOCITY (YRD) = +420791936+01
CROSS-TRACK POSITION (Z) = +19097827485
CROSS-TRACK VELOCITY (ZRD) = +37809677+02

FIG. 8-8 (CON'T)
FINAL VALUES FOLLOW

TIME = .239703000000 + .003
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD
IN-TRACK POSITION (Xs) = .6346514800
IN-TRACK VELOCITY (Xs) = .31264904 + .09
RADIAL POSITION (Ys) = .15679213 + .09
RADIAL VELOCITY (Ys) = .95871849 + .02
CROSS-TRACK POSITION (Zs) = .19467820 + .08 CROSS-TRACK VELOCITY (Zs) = .18864412 + .03

RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL TIMES .23260869 + .03
EXTRACTED RANGE VECTOR

<table>
<thead>
<tr>
<th>POSITION REL TO PAYLOAD MODULE</th>
<th>VELOCITY REL TO PAYLOAD MODULE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xs</td>
<td>Ys</td>
</tr>
<tr>
<td>.15479247 + .01</td>
<td>.45765206 + .08</td>
</tr>
<tr>
<td>.19230071 + .09</td>
<td>.39999172 + .03</td>
</tr>
<tr>
<td>.95990187 + .01</td>
<td>.10244018 + .03</td>
</tr>
</tbody>
</table>

RESULTS OF TESTS ON ACCURACY OF SET-UP FOR FINAL APPROACH
ANGLES BETWEEN BODY XYZ AND TRACKING AXES
ROLL = .122497539 + .01 YAW = .107565140 + .01 PITCH = .5537048 + .00

POSITION TOLERANCE = .50000000 + .01 50000000 + .00 50000000 + .00
VELOCITY TOLERANCE = .50000000 + .00 50000000 + .00 50000000 + .00
ANGLE TOLERANCE (DEG) = .50000000 + .01 50000000 + .01 50000000 + .01
CURRENT POSITION = .50898988 + .01 .29021345 + .00 .6175971 + .01
CURRENT VELOCITY = .31249886 + .00 .95494172 + .02 .10244018 + .03

POSITION, VELOCITY, AND BODY ANGLES ARE ALL ACCEPTABLE.

PROPellANT REQUIRED IN RETRO MANEUVER = .54942932 + .01
NEW FINAL PROPellANT MASS FOR AUXILIARY SYSTEM = .59442523 + .02

FIG. 8-8 (CON'T)
THE FOLLOWING IS RELATIVE TO THE TARGET.

IN-TRACK POSITION (X) = .50000000+01
RADIAL POSITION (Y) = .2579464+01
CROSS-TRACK POSITION (Z) = .6817397+01

IN-TRACK VELOCITY (XVD) = .31294680+00
RADIAL VELOCITY (YVD) = .29545872+02
CROSS-TRACK VELOCITY (ZVD) = .19266468+03

DEFINING FINAL RANGE VECTOR

IN TRACK = -.50000000+01
RADIAL = -.00000000
CROSS TRACK = -.00000000

DEFINING FINAL VELOCITY VECTOR

IN TRACK = .30000000+00
RADIAL = .00000000
CROSS TRACK = .00000000

REMAINING TOTAL MASS = .10545254+00
REMAINING MAIN ENG PROP MASS = .02629394+03
REMAINING APS PROP MASS = .99842684+02
IF RETRO MANEUVER PERFORMED, APS FUEL MASS = .59492353+02

WEIGHT OF PROPELLANT CONSUMED IN DOCKING: LBS = .12409848+04
TOTAL DELTA-V = .19044724+02

EXTRAPOLATION OF POSITION AND VELOCITY TO FINAL DOCKED POSITION

TIME OF FINAL DOCK = .26329131+03
IN-TRACK POSITION (X) = .11210936+01
RADIAL POSITION (Y) = .42753657+00
CROSS-TRACK POSITION (Z) = .47212921+01

IN-TRACK VELOCITY (XVD) = .31294680+00
RADIAL VELOCITY (YVD) = .29545872+02
CROSS-TRACK VELOCITY (ZVD) = .19266468+03

MISS DISTANCES IN INCHES:

IN-TRACK POSITION MISS = .20000000
RADIAL POSITION MISS = .00582649+01
CROSS-TRACK MISS = .10377609+01

*** DOCKING MANEUVER COMPLETED ***

FIG. 8-8 (CON'T)
# DOCKING MANEUVER DATA

**SPACE YEB DOCKING STUDY**

**ATTITUDE CONTROL INTEGRATION STEP SIZE = 0.1**

**PROGRAM CONTROLS**

<table>
<thead>
<tr>
<th>Attitude Control Integration Step Size</th>
<th>Program Controls</th>
<th>Print Cycle</th>
<th>Max. Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ENGLISH UNITS WILL BE USED IN THIS RUN**

<table>
<thead>
<tr>
<th>GUIDANCE PARAMETERS</th>
<th>STANDOFF RANGE</th>
<th>LAT. ENG. SWITCH</th>
<th>LINES ONLY</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUIDANCE FILTER TIME CONSTANT</td>
<td>0.0999999992</td>
<td>0.0999999992</td>
<td>0.0999999992</td>
</tr>
</tbody>
</table>

**PROBABILITY PARAMETERS**

<table>
<thead>
<tr>
<th>MAIN ENG. ISP</th>
<th>AXIAL ENG. ISP</th>
<th>LATERAL ENG. ISP</th>
<th>MAIN ENG. THRUST</th>
<th>AXIAL ENG THRUST</th>
<th>LATERAL ENG THRUST</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0999999993</td>
<td>0.0999999993</td>
<td>0.0999999993</td>
<td>0.0999999993</td>
<td>0.0999999993</td>
<td>0.0999999993</td>
</tr>
</tbody>
</table>

**FIG. 8-9 COMPUTER OUTPUT - ENGLISH UNITS, DETAILED ATTITUDE CONTROL INPUT VARIABLES**
**Fig. 8-10 Computer Output - English Units, Detailed Attitude Control Data**
CONCLUSIONS

9.1 DOCKING CONTROL STRATEGIES

A position update (autonomous navigation) could be advantageous after the rendezvous injection burn if the autonomy level selected for the Tug is I or II.

Strategies are required in the event the Tug does not acquire the payload during the acquisition phase, or the docking aid for the final docking phase.

Impingement could be a very severe problem during docking or abort. The APS forward thruster should be disabled far from the Tug. The attitude control system logic should be mechanized so that no forward thruster will be fired in the payload vicinity. The effect on attitude accuracy and rate and total impulse should be studied to assess the impact of this mechanization including the cross-products of inertia and center of gravity offsets and travel. During the coast from the standoff point to latch-up all thrusters should be disabled except in the case of an emergency abort. If an abort is required only thruster normal to the x-axis should be used. A provision should be made to inspect the payload docking mechanism to see that it is not obstructed or damaged.

Low-G propellant slosh could be a very serious problem for the Tug. Potentially it could have an even greater effect on the vehicle than impingement. Analysis of this problem is strongly recommended.

A six by six Kalman sequential filter for the docking sensor data is recommended.
9.2 DOCKING SENSOR REQUIREMENTS

A position update capability would reduce the field of view requirements. For the specified rendezvous injection accuracies a minimum 143.72 KM (77.6NM) acquisition range is recommended.

9.3 DOCKING MECHANISM DESIGN

The androgynous international docking mechanism seem suitable for the Space Tug. The center-line miss distance specification should be made as large as possible.

9.4 ABORT

If an abort is required only thruster perpendicular to the vehicle x-axis should be fired. Additional impingement studies are necessary.

For a given payload configuration the driving parameters on the total impulse used for the abort are:

1. The docking mechanism position error allowance normal to the docking axis and the maximum latch-up velocity.

2. The translational control capability to reduce the velocity normal to the docking axis to a small value.

3. The time allowed for the redocking attempt.

4. The time available to clear the payload after the initiation of the abort burn. This time is simply the distance from the payload at the abort time divided by the docking velocity ($V_{DOCK}$).

The run down the docking axis to redock consumes the most APS total impulse for an abort.
Section 10
SUGGESTED FURTHER STUDIES

The suggested studies in this section would provide needed analysis to further define the requirements and configuration for the Space Tug and to provide support to the Aero-Astrionics Laboratory.

(1) Training at MSFC in the Use of LOCDOK
LOCDOK is a fairly complex simulation. Previous experience has shown that a minimum of two weeks of instruction and customer usage, at MSFC, is required to proficiently utilize a complex simulation.

The training will comprise lectures, supervision of runs by customer personnel, and aid in debugging problems.

(2) Program Modification
The documentation provided under the present contract is not detailed enough to permit experienced programmers to modify LOCDOK. Invariably, after a period of use, desirable changes and additions become evident. The necessary programming support can be provided to the Aero-Astrionics Laboratory.

(3) Incorporation of Low-G Propellant Slosh into the Space Tug Automatic Docking Simulation
Low-G propellant slosh could have a very large impact on the Space Tug Mission. Propellant slosh could affect the Tug mission capability and require redesign of the Tug subsystems. Lockheed Missiles & Space Company has been involved with low-G propellant slosh and propellant management systems for many years. In addition to extensive analytical efforts, Lockheed has written a technical brief, Ref. 15, that details the suggested effort.
(4) **Control System Modification**

The results of the impingement study have shown that it is undesirable to fire the forward thrusters in the vicinity of the payload. LOCDOK's detailed attitude control simulation should be modified to simulate and analyze the effect of this mechanization on the Tug's attitude control total impulse, pointing accuracy, and limit cycle rate.

(5) **Autonomous Navigation**

For higher autonomy levels, the Space Tug will probably require an autonomous navigation capability. A position update capability will reduce the FOV requirements for the docking sensor.

Table 10-1 shows potential concepts for autonomous navigation. It is assumed that stellar inertial reference, computing, and time reference capability are available for on-board navigation. Specifically, space vehicle navigation is performed with all positions and velocity computations done on board the vehicle. It is further assumed that a low-g accelerometer is considered in each of these approaches for purposes of measuring accelerations due to tank venting and other unscheduled vehicle perturbations. Certain of these sensor types (e.g., horizon sensor) can be considered for use during initialization and for backup. A block diagram for a typical orbit navigational system is shown in Fig. 10-1. Since three positions and three velocity coordinates must be corrected with perhaps only one or two measurements (range, for example, is just one measurement), the selection of how much correction to make to each state must follow an orderly process if the solution is to converge. The Kalman filter has the algorithms for the orderly "sequential filtering" of the measurements. Table 10-2 contains excerpts of Kalman filter, linear system, and noise equations that would have to be studied and implemented for autonomous navigation.

Another suggested study would determine the optimum Kalman filter for Space Tug. The study would include Kalman filter compatibility and possible use as a data filter for the docking sensor.
(6) Impingement Studies

A significant study would be the effects of impingement on some typical payloads. Payloads with solar panels, antenna, and other asymmetrical shapes should be examined. In addition, the impingement effects on the Tug itself which give rise to torques and high temperatures on the skin should be analyzed. This study would optimize, within the constraints specified by the customer, the cant angle of the APS thrusters parallel to the vehicle x-axis.

(7) APS Total Impulse Optimization

Section 2 allocates 411.9 Kg (908.8 lb.) of APS propellants at the start of docking. This allocation is marginal for a normal docking and would not be sufficient if an abort or non-nominal trajectory occurred. It is suggested that a study to optimize the total APS impulse be made and the allocation of propellant be reassessed.
<table>
<thead>
<tr>
<th>NAVIGATION CONCEPT</th>
<th>BASIC NAVIGATION SENSOR (ON SPACECRAFT)</th>
<th>SPECIAL EQUIPMENT ON GROUND OR NAV/DATA RELAY SATELLITE</th>
<th>DATA TRANSMISSION TO GROUND FOR NAVIGATION</th>
<th>SPACECRAFT ATTITUDE DETERMINATION</th>
<th>AUXILIARY SENSING</th>
<th>AUTO-NOMY LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextant - Timation Augmented Subtended Angles Between Star Sightings and Either Known or Unknown Landmarks, Periodic Update by Measuring Time Difference of Arrival of Coded Pulses with Synchronized Clock</td>
<td>Landmark Tracking Telescope and Star Tracker (May Be One Integrated Sensor)</td>
<td>Transmitter of Coded Pulses Giving Time of Transmission, Transmitter Location and Clock Calibration Data</td>
<td>None</td>
<td>Inertial Frame Defined by Star Sightings, (May Be Part of Integrated Sensor)</td>
<td>Receiver of Timation Coded Pulses for Periodic Updates and Horizon Sensor for Initialization, (May Both Be Part of Integrated Sensor)</td>
<td>II</td>
</tr>
<tr>
<td>Navigation by Ground Beacon</td>
<td>Transceiver (UHF) With Range Detection; Measures Range to Ground Transponder, (Also Range Rate; See Auxiliary Device)</td>
<td>Transponders Placed in Near Orbit Path</td>
<td>Coded Beacon Signal</td>
<td>None Required for Navigation</td>
<td>Measure Range Rate to Ground Transponder</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>a. Three or 4 Antennas Located 10-1 Apart Receiver(s) Phase Detecting Circuits for Differential Ranging; Measures Angle From Ground Station to Spacecraft</td>
<td>a. Transmitters of Known Locations and Frequencies on Earth Surface</td>
<td>b. None Required for Navigation</td>
<td>b. None Required for Navigation</td>
<td>b. Radar Altimeter</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>b. Receiver (with Phase Detection Circuits for Differential Ranging) Measures Angle From Ground Station to Spacecraft</td>
<td>b. Groups of 3 Synchronized Ground Transmitters Near the Orbit Path</td>
<td></td>
<td></td>
<td>Low-G Accelerometer</td>
<td>II</td>
</tr>
<tr>
<td>One Way Doppler</td>
<td>Existing 5-Band Receiver</td>
<td>None (Use Existing 5-Band Transmitter)</td>
<td>None</td>
<td>Inertial Defined by Star Sighting</td>
<td>Low-G Accelerometer</td>
<td>II</td>
</tr>
<tr>
<td>Ground Tracking</td>
<td>5-Band or SOLS Transponders With Ranging</td>
<td>5-Band or SOLS Transponders, Tracking Antennas, Ground Processor</td>
<td>Coded Ranging Signal Modulating Down-Link Carrier</td>
<td>Inertial Defined by Star Sighting</td>
<td>Radar Altimeter</td>
<td>II</td>
</tr>
<tr>
<td>Special Earth Targets</td>
<td>Tracking Telescope Measures Angles to Earth Target</td>
<td>Gimballed Laser Transmitters Placed Near Orbit Path</td>
<td>Either of Two Attitude Reference Frames</td>
<td>B2. Local Vertical/Orbit Plane Frame Defined by Horizon Sensor</td>
<td>Low-G Accelerometer</td>
<td>III</td>
</tr>
<tr>
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</table>
FIG. 10-1  TYPICAL ORBIT NAVIGATION SYSTEM BLOCK DIAGRAM
TABLE 10.2
TYPICAL KALMAN EQUATIONS

FILTER EQUATIONS FORM

<table>
<thead>
<tr>
<th>Solved-For Parameters</th>
<th>Considered Parameters (ρ, m)</th>
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</thead>
<tbody>
<tr>
<td>( \hat{x}^s = \hat{x} + P^s P^{-1} G u + f )</td>
<td>( \hat{x}_c^s = \hat{x}_s^c + J P )</td>
</tr>
<tr>
<td>( P^s = \hat{P} \hat{P}^T + Q )</td>
<td>( P_c^s = P_c^s - \hat{P} \hat{C}_p^T G^T - G \hat{C}_p^T \hat{P} + G \hat{D} \hat{G}^T )</td>
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</tbody>
</table>

LINEAR SYSTEM EQUATIONS STRUCTURE

<table>
<thead>
<tr>
<th>STATE VECTOR COMPONENTS</th>
<th>( \Sigma^u )</th>
<th>( \Sigma^r )</th>
<th>( \Sigma^s )</th>
<th>( \Sigma^w )</th>
<th>( \Sigma^x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma^u )</td>
<td>( \Sigma^r )</td>
<td>( \Sigma^s )</td>
<td>( \Sigma^w )</td>
<td>( \Sigma^x )</td>
<td></td>
</tr>
<tr>
<td>( \Sigma^u )</td>
<td>( \Sigma^r )</td>
<td>( \Sigma^s )</td>
<td>( \Sigma^w )</td>
<td>( \Sigma^x )</td>
<td></td>
</tr>
<tr>
<td>( \Sigma^u )</td>
<td>( \Sigma^r )</td>
<td>( \Sigma^s )</td>
<td>( \Sigma^w )</td>
<td>( \Sigma^x )</td>
<td></td>
</tr>
</tbody>
</table>

NOISE EQUATIONS

<table>
<thead>
<tr>
<th>Measurement Noise</th>
<th>Plant Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E</td>
<td>n(t_i)</td>
</tr>
</tbody>
</table>
Section 11

REFERENCE


18. LMSC, Gemini Agena Target Vehicle Familiarization HDBK, LMSC-A602521, April 1964.


