SPACE TUG AUTOMATIC DOCKING CONTROL STUDY

(NASA-CR-120578) SPACE TUG AUTOMATIC DOCKING CONTROL STUDY Final Report (Lockheed Missiles and Space Co.) 125 p HC $5.25 CSCL 22B
N75-14820
Unclas
G3/18 08061

FINAL REPORT

CONTRACT NAS 8-29747

LMSC-D424228

LOCKHEED

LOCKHEED MISSILES & SPACE COMPANY, INC.

A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

LMSC-D424228
31 October 1974

SPACE TUG AUTOMATIC DOCKING CONTROL STUDY

FINAL REPORT

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

Contract No. NAS8-29747

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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Systems Dynamics Laboratory - ED15
Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812
Telephone (205) 453-2470

CONTENTS

LIST OF ILLUSTRATIONS

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LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

Section 1
INTRODUCTION

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)

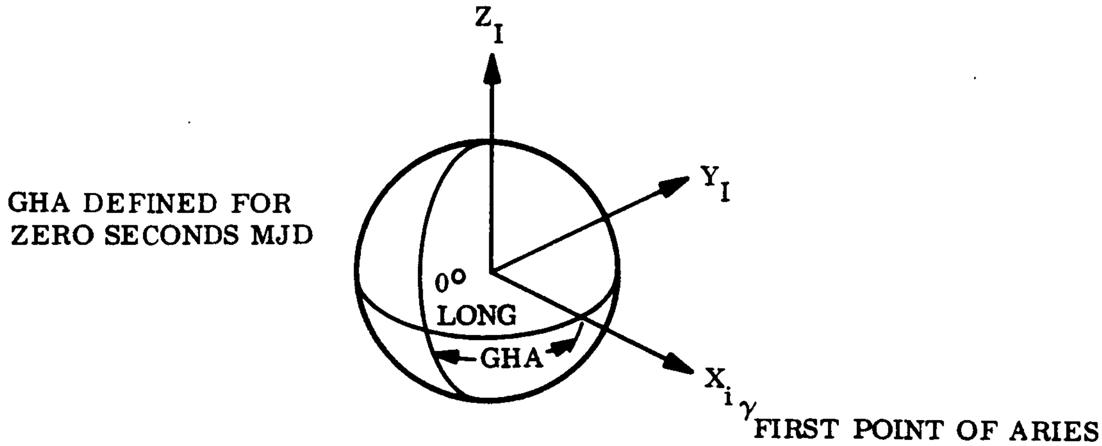

FIG. 1.1 INERTIAL COORDINATE SYSTEM

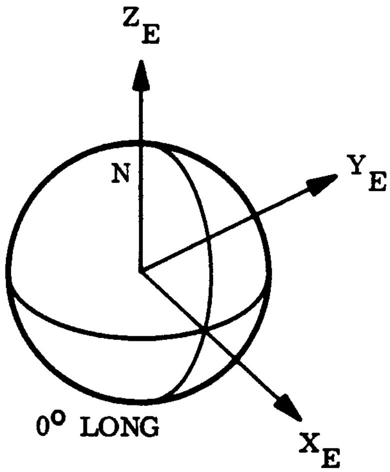

FIG. 1.2 EARTH-CENTERED COORDINATE SYSTEM

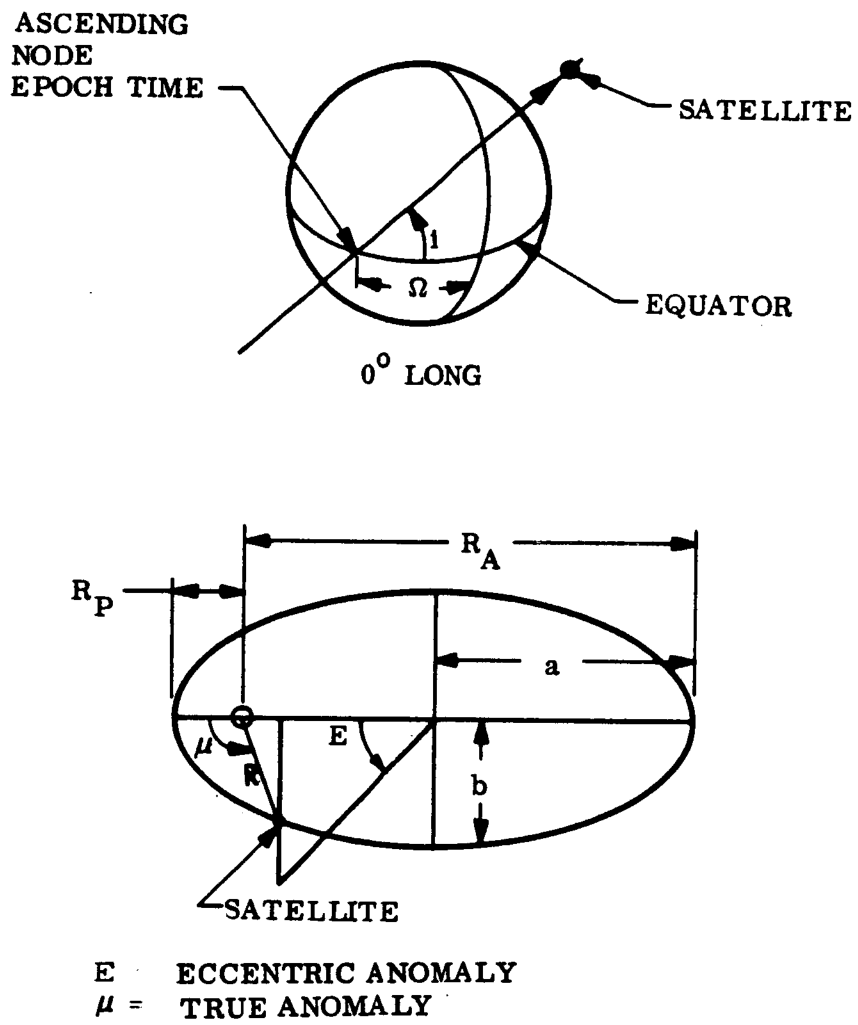

FIG. 1-3 ORBITAL COORDINATE SYSTEM

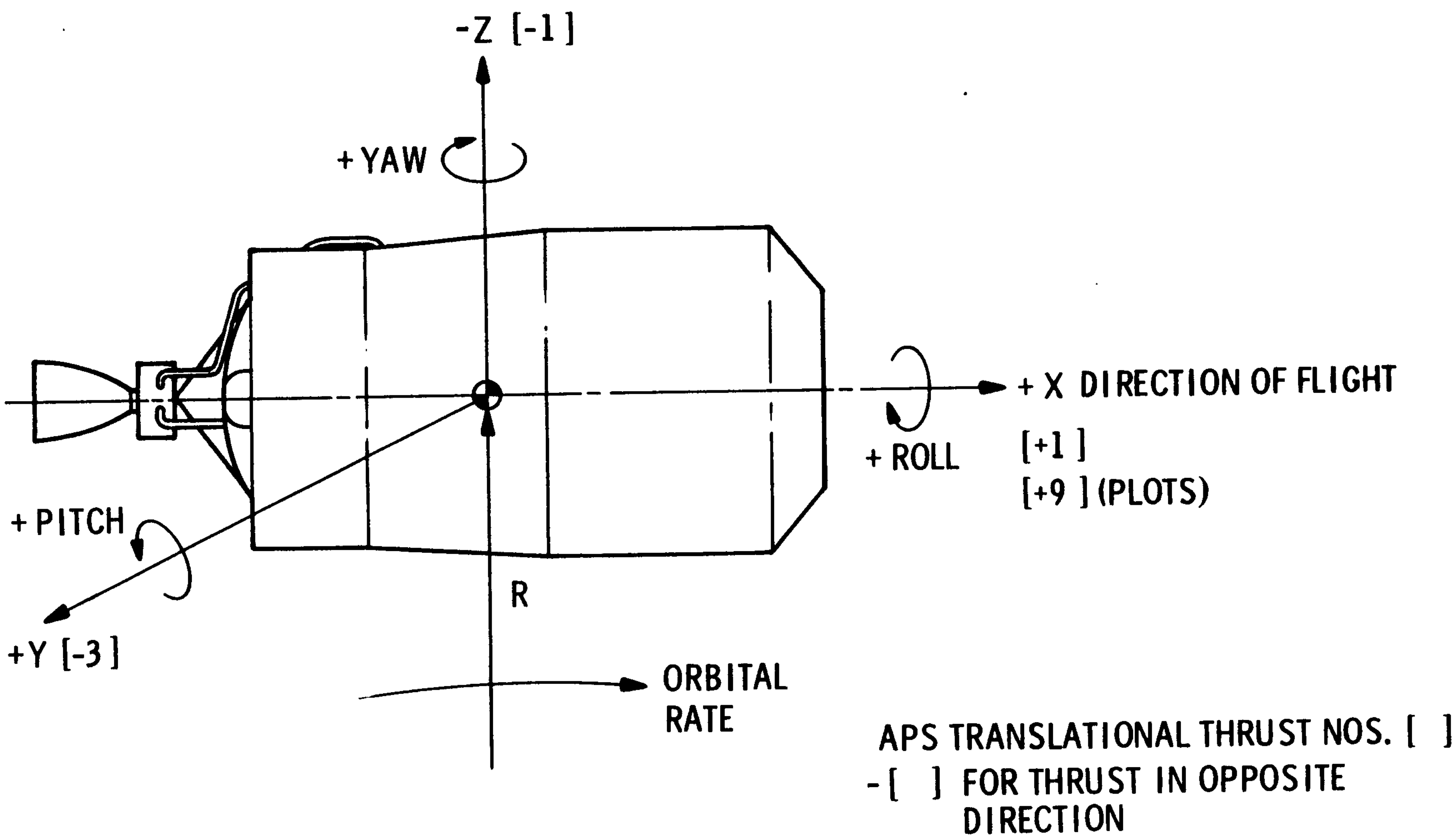

Fig. 1-4 Vehicle Coordinate System

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.

LOCDOK Printout

Axial engine No. = 1, + thrust
- 1, - thrust

$$\text{Lateral engines No.} = \begin{bmatrix} 1, + z \text{ thrust} \\ -1, - z \text{ thrust} \end{bmatrix} + 3 \begin{bmatrix} +1, -y \text{ thrust} \\ -1, +y \text{ thrust} \end{bmatrix}$$

On the 4020 plots

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

1.4 VEHICLE CONFIGURATION

The Baseline Tug Configuration used in this study is shown in Fig. 1-5.

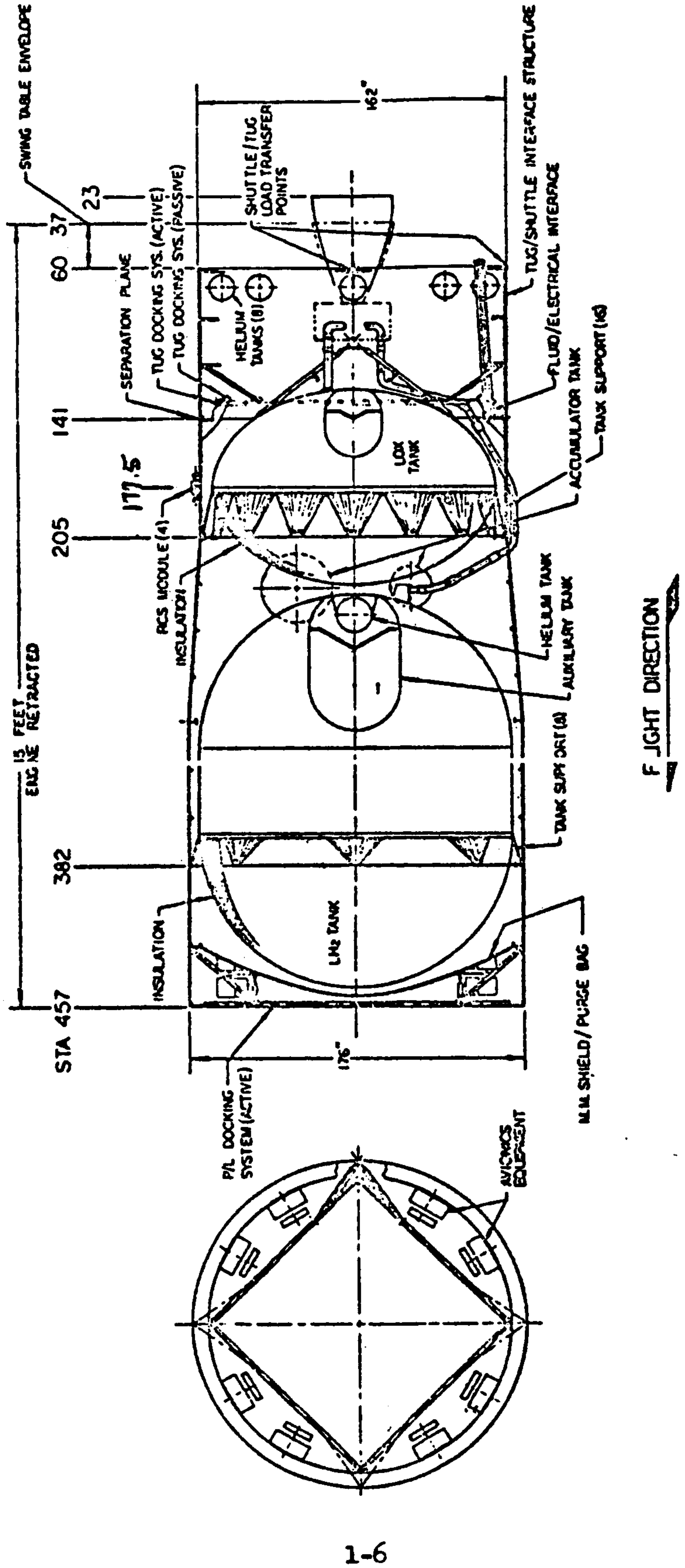

Fig. 1-5 BASELINE TUG OVERALL CONFIGURATION

1.5 CONVERSIONS TO SI UNITS*

Units From	To	Constants
Degrees (deg)	Radians (rad)	deg* 0.01745329
Inches (in.)	centimeters (cm)	in.* 2.54
Feet (ft)	meters (m)	ft* 0.3048
Nautical Miles (nmi)	kilometers (km)	nmi* 1.852
Pounds, force (lb_f)	newtons (n)	lb* 4.44822
Mass (slugs)	kilograms (kg)	slug* 14.5939
Torque ($ft\text{-}lb_f$)	meter-newtons (m-n)	ft-lb* 1.35582
Moment of Inertia ($slug\text{-}ft^2$)	kilogram-meters^2 ($kg\text{-}m^2$)	$slug\text{-}ft^2$* 1.35582
Pounds, Mass (lb_m)	kilograms (kg)	lb_m* 0.4532267

*Conversion Constants from NASA SP-7012, Ref. 14.

Section 2
STANDARD CHARACTERISTICS FOR ANALYSIS

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

	kg	(lb)
Dry Weight	2,341.4	5,166
Max Retrieval Wt for S&E Tug	1,164.8	2,570
Payload Interface	669.0	1,476
Start Docking Wt	14,810.5	32,678
Burnout Weight	2,815.9	6,213
Total Propellants & Gases	23,185.2	52,921
Ignition Weight	26,326.5	58,086.8

2.2.2 Moments of Inertia and C.G.

	Begin Orbit		Start of Docking		DRY	
	$kg\text{-}m^2$	$(slug\text{-}ft^2)$	$kg\text{-}m^2$	$(slug\text{-}ft^2)$	$kg\text{-}m^2$	$(slug\text{-}ft^2)$
Pitch (Iyy)	93,742.8	69,141	58,907.7	43,448	24,071.2	17,754
Yaw (Izz)	93,437.7	68,916	58,594.4	43,217	23,751.3	17,518
Roll (Ixx)	7,819.0	5,767	7,157.4	5,279	6,495.7	4,791
Tug C.G. (tug station)	518.2 cm	204 (in.)	541.0 cm	213 (in.)	612.1 cm	241 (in.)

2.2.3 Attitude Control

	rad	(deg)
Deadbands (total)		
Roll, pitch, yaw	0.008725	0.5
Moment Arms	m	(ft)
Pitch, Yaw	0.90169	2.9583
Roll	2.0574	6.75

*Baseline Tug Definition Document Rev. A, 26 June 1972 as amended by data for use on Space Tug Automatic Docking Control, 12 December 1973, Homer Pack.

Attitude Control Gains

	Position		Rate	
	n/rad	(lb_f/rad)	n/rad/sec	(lb_f/rad/sec)
Pitch	656.664	147.624	13,133.28	2,952.48
Yaw	653.163	146.837	13,063.27	2,936.74
Roll	34.972	7.8620	699.44	157.24

2.2.4 Propulsion

2.2.4.1 Engines

	I_{min} (bit) (nominal)		I_{SP} (nominal)	Thrust (nominal)		I_T (Tail off) (nominal)		I_T (Uncert) (3-Sigma)	
	n-sec	(lb_f-sec)	sec	n	(lb_f)	n-sec	(lb_f-sec)	n-sec	(lb_f-sec)
Main Engine	6,672.33	1,500	444	66,723.3	15,000	14,234.3	3,200	1,423.43	320
APS (For-Aft)	11.12	2.5	230	444.8	100	22.2	5	2.22	.5
APS (Lat)	11.12	2.5	230	444.8	100	22.2	5	2.22	.5

2.2.4.2 Propellants, Usable

	Start Orbit				Start Docking			
	Impulse		Mass	Weight	Impulse		Mass	Weight
	n-sec	(lb_f-sec)	kg	(lb_m)	n-sec	(lb_f-sec)	kg	(lb_m)
Main	99,533,370	22,376,000	22,842.6	50,400	52,539,683	11,811,395	12,057.6	26,604
APS (For-Aft) / APS (Lateral)	913,219.6	205,300	412.9	911	910,314.9	204,647	411.9	908.8

2.2.5 Docking Sensor (Scanning Laser Radar) (Ref. 16)

PRF	1 KHz	
Data Sampling Rate	16 per second	
Gimbal Freedom		
	rad	(deg)
Azimuth	0.5235	30
Elevation	0.5235	30
Gimbal Rates & Acceleration		
Angular Rate (Acq. Aver.)	0.003713 rad/sec;	0.2128 (deg/sec)
Max Angular Rate (Tracking)	0.001745	1.0 (deg/sec)
Angular Acceleration	N/A	
Acquisition Range (99% probability of acquisition)	143.72 km; (77.6) nmi**	
Acquisition Scan Pattern		
	rad	(deg)
Azimuth	0.5235	30
Elevation	0.5235	30
Search Frame Time	1.41376 sec	
Track Frame Time	0.064 sec	
	rad	(deg)
Beamwidth	0.0001745	0.1
Bandwidth		50 Hertz
	m	(ft)
Range Resolution	0.09144	0.3
	rad	(deg)
Angle Resolution	0.0000436	0.0025
Range Accuracy (3-sigma Smoothed Data)	0.01% of R	
Angle Accuracy (3-sigma Smoothed Data)	0.0008725 rad;	.05°

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.) (σ_R) σ_R = 23.8355

AZ, EL (Std. Dev.) (σ_R) σ_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.) (σ_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)

	Position		Velocity	
	km	(nmi)	m/sec	(ft/sec)
Tangential	55.56	30.0	3.6576	12.0
Radial	59.26	32.0	4.2672	14.0
Normal	59.26	32.0	4.2672	14.0

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	± 005235 rad (± 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 Tech-~~ nical Information Center interrogated the DCC 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

Prelim. Req. Study, Vol. III, Payload Retrieval
McDonnell-Douglas, Huntington Beach
AD-903 092L Unc. Vol. III

Vol. I Mgt. of Tech. Summary, AD-903 0906 Unc.
Report No. 19DC-G3702 - Vol. 1,3
Contract F04701-72-C-0304
SAMSO TR-72-202-Vol, 1,3

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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 F04701-71-C-0171

SAMSO 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 F04701-70-C-0059

TERMINAL REND. CONSIDERATIONS FOR THE STS

AD-875 194L

Aerospace

Report No. TDR-0059 (6758-07)-6

Contract F04701-70-C-0059

RENDEZVOUS TRAJ. VOL. I

AD-722 890

Report No. DDC-TAS-70-85-1

AD-515 440

Rend. Traj. Vol. II No. DDC-TAS-70-85-2

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

SAMSO TR-71-123 Vol. 9

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

Tech. Report MOR-70-2, March 1970

Bodley, C. S., and A. C. Park

Final Report

Contract NAS8-21280, Martin Corp.

SPACE SHUTTLE VEHICLE AUTOMATIC DOCKING STUDY

Report No. NASA-CR-115248, E-2606

Author: Blanchard, E. P. Hutchinson, R. C. Johnson, I. B.

Final Report

A3925K3 Fld: 22A, 84A STAR1003 - Mass. Inst. of Tech., Cambridge

Oct 71 84p

Contract: NAS9-10268, DSR Proj. 55-40800

AUTOMATIC RENDEZVOUS & DOCKING FINAL REPORT

Report No: NASA-CR-103037

Ayyar, S. A., Flom, T. E. - ITT Aerospace/Optical Div., San Fernando, Ca.

A1984F1 FLD: 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.

A0172H2 BLD: 13E, 22B, 922, 944 STAR0808

21 Nov 69 33p

Report No: NASA-CASE-MSC-15474-1, US-SN-878731

Contract: NAS9-150

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. FTD-HT-23-1346-68

Edited trans. of mono. Congress of the International Astronautical Federation (19th) New Yor, 1968. Report n.p., 1968 p1-24 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

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DOCKING IN SPACE A COMPLEX PROBLEM

Joint Publications Research Service, Washington, D.C. (193 300)

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. FTD-HT-23-1606-67

Edited trans. from Pravda, Moscow (USSR) p3, 1 Nov 67, by R. Zeccola

RENDEZVOUS IN SPACE. HOW THE AUTOMATIC SATELLITES FOUND EACH OTHER IN ORBIT

Foreign Technology Div Wright-Patterson AFB Ohio (141600)

Author: Marinin, Yurii

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) p1, 31 Oct 67, by R. Zeccola

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

Techtran Corp, Glen Burnie, Md.

Author: Raushenbakh, V. K.

Avtomaticheskaya Stykovka W Kosmose I Yeye Svyaz's Teoriyey I

Pracktikoy 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

Report No. NASA-TM-X-68368, MSC-04217-REV-B

Misc O revised

FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON AFB OHIO (141600)

Author: Lebendev, A. A., Sokolov, V. B.

A340314 FLD: 22A, 22C, 84A, 84D USGRADR7203

30 Aug 71 503p

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p1-366, by Charles T. Ostertag

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NASA, MSC, Houston, Tex.

A3062A4 FLD: 17G, 84A STAR0319

15 Apr 71 227p

Report No. NASA-TM-X-67215, MSC-04217-VOL-3

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.

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4 Nov 68 46p

Report No. NASA-CR-92493, TRW-11176-K066-R0-00

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 FLD: 22C USGRDRA6904

16 Apr 68 9p

Report No. FTD-HT-23-229-68

Edited trans. of Aviatsionnyi Inst, Kazan Trudy (USSR) n89

p41-47 1965, by J. Miller

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 STAR0606

1965 33p

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Contract: NAS7-100

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SIXTH AAP-4 UNMANNED RENDEZVOUS MEETING AT MSC, JUNE 27, 1968

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A/Guffee, C. O.

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POSSIBLE APPROACH TO PHASING FOR UNMANNED RENDEZVOUS, CASE 610

68X8 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

NGR-39-009-162 71/09/25 25 pages

(Development and Analysis of Techniques for Retrieving Uncooperative Spinning Objects in Space Environment)

A/Keplan, M. H.

Pennsylvania State University, University Park. (Dept. of Aerospace Engineering)

Presented at the 22nd Congress of the International Astronautical Fed, Brussels, 20-25 Sept. 1971

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73A1 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
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71A3 70309 Issue 19 Page 3150 Category 31 71/00/00 12 pages
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Structure, Hookup System, Docking and Propellant Supply)
A/Porru, M. (AA/Fiat S.P.A., Division Aviazione, Turin, Italy
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71A3 5051 Issue 17 Page 2772 Category 21 71/00/00 540 pages
NASA Marshall Space Flight Center, Huntsville, Ala., Feb 23-25, 1971
Proceedings (Space Shuttle, Space Station and Nuclear Shuttle
Navigation-Conference, Huntsville, Ala., Feb 1971)

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71A1 9526 Issue 7 Page 1154 Category 21 70/00/00 815 pages
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72N7 5159 68/00/00 22 pages
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General Electric Co., Philadelphia, Pa (Missile & Space Div)

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72N1 3391 Issue 4 Page 485 Category 15 NASA-SP-282 71/00/00
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Methods for Aerospace Mechanisms Used in Orbital and Space Flights)

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69N1 5337 Issue 5 Page 899 Category 31 AD-678411
FTD-HT-23-1605-67 67/12/06
(Docking of Cosmos-186 and Cosmos-187)
A/Martinin, Y.
Air Force Systems Command, Wright-Patterson AFB, Ohio
(Foreign Technology Div.)

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69N1 0561 Issue 1 Page 176 Category 31 NASA-CR-97483
NSR-44-005-059 68/09/00 355 pages
(Preliminary System Design for Satellite Servicing Vehicles - Manned and Unmanned Models)
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APPLICATIONS OF RADAR TO SPACECRAFT AND SPACEFLIGHT

69N3 6488 Issue 23 Page 4020 Category 7 NASA-TM-X-60473
68/00/00 6 pages
(Spacecraft Radar Present and Future Applications in Rendezvous and Soft Landing)
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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 $\pm$ 1.852 (1 nmi) 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 nonlinear 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 X 1 vector representing the actual measurements, w_k is the ℓ X 1 vector representing the uncorrelated noise on the measurements, x is the mX1 vector representing the state of the system, $h_k(x)$ is an ℓ X 1 vector representing perfect measurements, and R_k is the ℓ X ℓ covariance matrix of the noise

$$z_k = h_k(x) + w_k \tag{4-1}$$

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

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

$$E\left[w_k\right] = 0 \tag{4-2}$$

$$\text{cov}\left[w_j\ w_k\right] = 0 \qquad j \neq k$$

The best estimate of the state $\hat{x}$ can be written as shown below, where H_k is the ℓ X m matrix of partial derivatives and $\hat{x}_0$ is the initial nominal value of the state

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

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

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

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

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.

$$\hat{x} = M^{-1}\left\{\sum_{k=1}^{N} H_k' R_k^{-1} z_k\right\}$$

$$M = \sum_{k=1}^{N} H_k' R_k^{-1} H_k \tag{4-4}$$

If there is prior information that the state x has a value $\bar{x}_0$ 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 = 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.

$$x_{k+1} = \Phi_{k+1} x_k + u_k \tag{4-5}$$

The linear measurements obtained from the system are given by another set of matrix equations.

$$z_k = H_k \;\; x_k \;\bullet\; W_k \qquad \text{for } k = 1,2,\ldots,N \tag{4-6}$$

The matrices Φ (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:

$$E(u_j u_k') = Q_k \quad \text{if } j = k \text{ and zero otherwise} \tag{4-7}$$

$$E(v_j w_k') \quad R_k \quad \text{if } j = k \text{ and zero otherwise}$$

$$E(u_j w_k') = 0$$

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.

TABLE 4-2

PARTIALS OF POSITION AND VELOCITY AT A LATER TIME WITH RESPECT TO POSITION AND VELOCITY AT AN EARLIER TIME. Φ (TRANSITION MATRIX)

$$\begin{bmatrix}
\frac{\partial (rad)_t}{\partial (rad)_0} & \frac{\partial (rad)_t}{\partial (IT)_0} & \frac{\partial (rad)_t}{\partial (CT)_0} & \frac{\partial (rad)_t}{\partial (V_{rad})} & \frac{\partial (rad)_t}{\partial (V_{IT})_0} & \frac{\partial (rad)_t}{\partial (V_{CT})_0} \\
\frac{\partial (IT)_t}{\partial (rad)_0} & \frac{\partial (IT)_t}{\partial (IT)_0} & \frac{\partial (IT)_t}{\partial (CT)_0} & \frac{\partial (IT)_t}{\partial (V_{rad})_0} & \frac{\partial (IT)_t}{\partial (V_{IT})_0} & \frac{\partial (IT)_t}{\partial (V_{CT})_0} \\
\frac{\partial (CT)_t}{\partial (rad)_0} & \frac{\partial (CT)_t}{\partial (IT)_0} & \frac{\partial (CT)_t}{\partial (CT)_0} & \frac{\partial (CT)_t}{\partial (V_{rad})_0} & \frac{\partial (CT)_t}{\partial (V_{IT})_0} & \frac{\partial (CT)_t}{\partial (V_{CT})_0} \\
\frac{\partial (V_{rad})_t}{\partial (rad)_0} & \frac{\partial (V_{rad})_t}{\partial (IT)_0} & \frac{\partial (V_{rad})_t}{\partial (CT)_0} & \frac{\partial (V_{rad})_t}{\partial (V_{rad})_0} & \frac{\partial (V_{rad})_t}{\partial (V_{IT})_0} & \frac{\partial (V_{rad})_t}{\partial (V_{CT})_0} \\
\frac{\partial (V_{IT})_t}{\partial (rad)_0} & \frac{\partial (V_{IT})_t}{\partial (IT)_0} & \frac{\partial (V_{IT})_t}{\partial (CT)_0} & \frac{\partial (V_{IT})_t}{\partial (V_{rad})_0} & \frac{\partial (V_{IT})_t}{\partial (V_{IT})_0} & \frac{\partial (V_{IT})_t}{\partial (V_{CT})_0} \\
\frac{\partial (V_{CT})_t}{\partial (rad)_0} & \frac{\partial (V_{CT})_t}{\partial (IT)_0} & \frac{\partial (V_{CT})_t}{\partial (CT)_0} & \frac{\partial (V_{CT})_t}{\partial (V_{rad})_0} & \frac{\partial (V_{CT})_t}{\partial (V_{IT})_0} & \frac{\partial (V_{CT})_t}{\partial (V_{CT})_0}
\end{bmatrix} = \begin{bmatrix} \Phi \end{bmatrix}$$

TABLE 4-3

TRANSITION MATRIX

$$\begin{bmatrix} 1.0 & -6 \text{ Sin } Wt+6 \text{ } Wt & 0.0 & \frac{4}{W} \text{ Sin } Wt-3t & \frac{-2}{W} \text{ Cos } Wt+2 & 0.0 \\ 0.0 & 1.0 & 0.0 & \frac{2}{W} \text{ Cos } Wt-\frac{2}{W} & \frac{1}{W} \text{ Sin } Wt & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & t \\ 0.0 & -6W \text{ Cos } Wt+6W & 0.0 & 1.0 & 2 \text{ Sin } Wt & 0.0 \\ 0.0 & 3W \text{ Sin } Wt & 0.0 & -2 \text{ Sin } Wt & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1 \end{bmatrix} = \begin{bmatrix} \Phi \end{bmatrix}$$

TABLE 4-4

MATRIX OF PARTIAL MEASUREMENTS WITH RESPECT TO THE ORBITAL FRAME

$$[H] = \begin{bmatrix} \partial S/\partial \text{rad} & \partial S/\partial IT & \partial S/\partial CT \\ \partial El/\partial \text{rad} & \partial El/\partial IT & \partial El/\partial CT \\ \partial Az/\partial \text{rad} & \partial Az/\partial IT & \partial Az/\partial CT \end{bmatrix}$$

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

where

S = range

Rad = radial position difference

IT = In-track position difference

El = Elevation angle

Az = 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:

$$P_{k/j} = E(x_k - x_{k/j})(x_k - \hat{x}_{k/j})' \tag{4-8}$$

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.

$$\begin{aligned} \hat{x}_{k/k} &= \hat{x}_{k/k-1} + B_k(z_k - H_k \ \hat{x}_{k/k-1}) \\ B_k &= P_{k/k-1} \ H_k(H_k \ P_{k/k-1} \ H_k' + R_k)^{-1} \\ \hat{x}_{k+1/k} &= \Phi_{\ k+1} \ \hat{x}_{k/k} \end{aligned} \tag{4-9}$$

The covariance matrix P can also be calculated sequentially:

$$\begin{aligned} P_{k/k} &= (I - B_k \ H_k) \ P_{k/k-1} \\ P_{k+1/k} &= \ \Phi_{\ k+1} \ P_{k/k} \quad {}'_{k+1} + Q_k \end{aligned} \tag{4-10}$$

The initial conditions for the filtering solution are based on the <u>a priori</u> information, which is that the state variable x_1 has a known mean, $\bar{x}_0$, and covariance $\bar{P}_0$.

$$E(x_1) = x_0 = \hat{x}_{1/0}$$

$$E(x_1 - \bar{x}_0)(x_1 - \bar{x}_0)' = \bar{P}_0 = P_{1/0} \tag{4-11}$$

For computational reasons, it is necessary that the matrix $\bar{P}_0$ be non-singular. If the actual a priori information is not sufficient to make $\bar{P}_0$ 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:

$$P^{-1}_{k/k} = P^{-1}_{k/k-1} + H_k \; R^{-1}_k \; H_k$$

$$P^{-1}_{k/k} \; \hat{x}_{k/k} = P^{-1}_{k/k-1} \; \hat{x}_{k/k-1} + H_k \; R^{-1}_k \; z_k \tag{4-12}$$

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

$$B_k = P_{k/k} \; H'_k \; R^{-1}_k \tag{4-13}$$

TABLE 4-1

AUTONOMOUS DOCKING PHASES

PHASE 1 RENDEZVOUS INJECTION BURN	PHASE 2 REORIENTATION	PHASE 3 ACQUISITION OF PAYLOAD	PHASE 4 CROSS TRANSFER TO DOCKING AXIS	PHASE 5 TRANSFER DOWN DOCKING AXIS	PHASE 6 EVAL. AT THE STANDOFF POINT	PHASE 7 COAST TO LATCHUP
GUIDANCE ERRORS ATT ERRORS AIM POINT CONSIDERATIONS A. SUN ILLUM OF PAYLOAD B. NO SUN, MOON, OR EARTH IN FOV C. SAFETY NO POSSIBLE IMPACT OF PAYLOAD D. PERFORMANCE OPTIMIZATION	COMPUTATION OF ATTITUDE COMMANDS TO POINT CENTER OF FOV AT CENTER OF UNCERTAINTY VOL. FOR PAYLOAD ROTATION OF TUG CHECK FOR SUN, MOON, EARTH IN FOV	ACQUISITION A. RANGE VS GUID ACC B. FOV VS GUID & ATT ACC C. RANGE VS PAYLOAD ILLUMANENCE D. MULTIPLE AND SPURIOUS TGTS E. PAYLOAD SCINTILLATION (AMPLITUDE) F. ASPECT ANGLES & OPTIMIZING ACQ., I.E., ORIENT ALONG LARGE DISP. AXIS G. ACQ TIME REQ H. SAFETY NO ACQUISITION SEARCH METHOD A. ON-BOARD – LWIR – MICROWAVE B. GRND UPDATE – OPTICAL – STDN/SGLS – SPADATS/SAS LOSS OF LOCK-ON REACQ METHODS SAFETY REQUIREMENTS FOR NO ACQ OR LOSS OF LOCK-LOCK-ON	AIM-POINT REQS (INCLD SAFETY) TRANSFER OPT A. TIME B. PROPELLANT C. POWER SENSOR DATA PROCESSING TV REMOTE BACKUP CONSIDERATIONS ACQ OF DOCKING RETRO REFLECTORS A. NO ACQ – CIRCUM-NAV – GRD ASST – ACQ AIDS TRANSFER OPTIMIZATION A. TIME B. PROPELLANT C. POWER	STANDOFF POINT REQ A. BURNS NEAR PAYLOAD B. EVALUATION C. DOCKING ERRORS D. PROPELLANT SLOSH ABORT CONSIDERATIONS TV REMOTE BACKUP CONSIDERATION FIRM CONSIDERATIONS NON-NOMINAL PAYLOADS A. SLOWLY ROTATING B. DAMAGED PAYLOAD PROPELLANT SLOSH EFFECTS	ABORT REQMTS A. BEST METHOD(S) TO ABORT, I.E., RETRO THRST VS LATERAL THRUST B. ABORT EFFORTS ON EFFECTS – PAYLOAD – TUG, I.E., PROP, TIME LINES, ETC. C. POSITION, RATE, ANGLE, ANGLE RATE REQ D. DAMAGED PAYLOAD TV REMOTE BACKUP CONSIDERATIONS	EFFECTS OF BURN, I.E., IMPINGEMENT SENSOR FOV CONSIDERATIONS A. SENSOR VS REFLECTOR PLACEMENT PROPELLANT SLOSH EFFECTS TV REMOTE BACKUP REQUIREMENTS ABORT REQMTS (INCLUD TUG FAILURE)

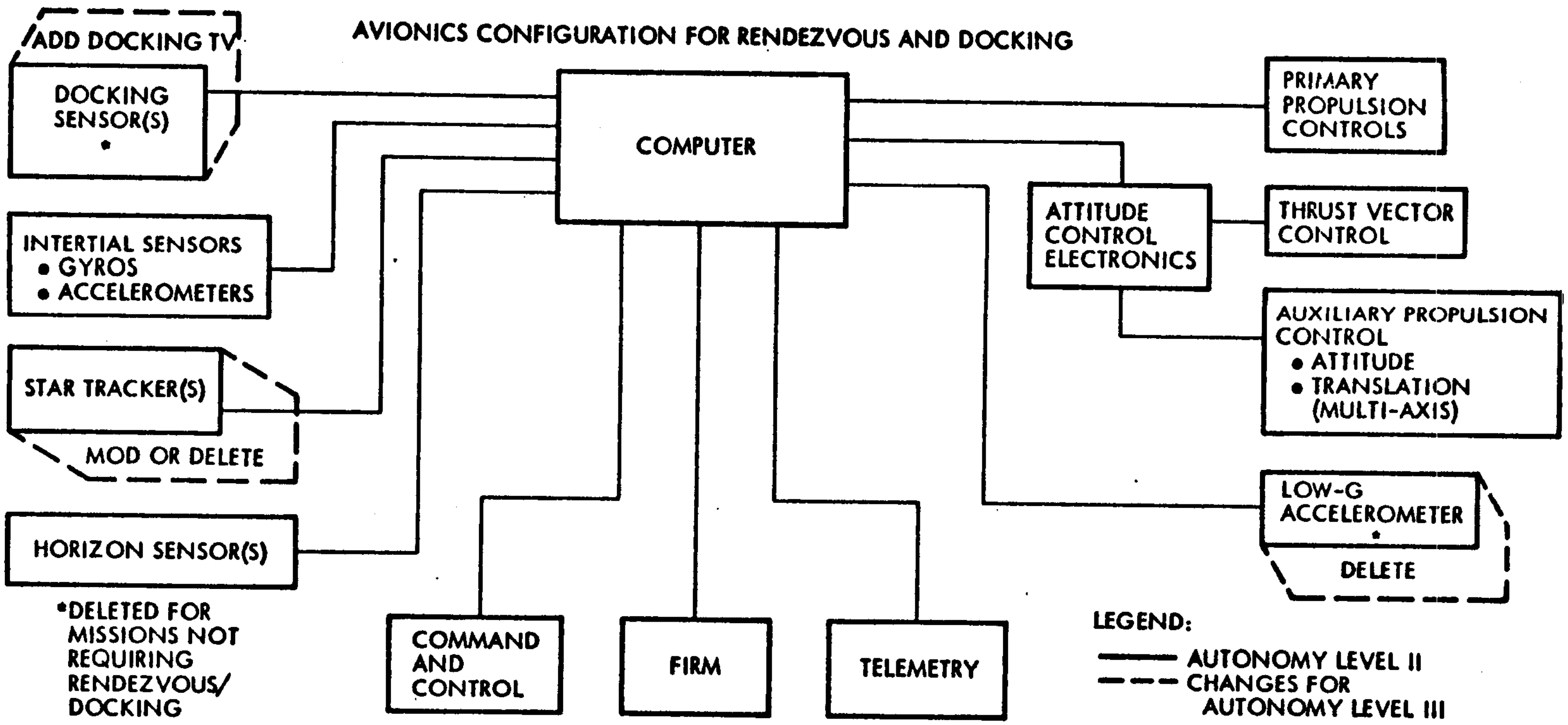

FIG. 4-1 AVIONICS CONFIGURATION FOR RENDEZVOUS AND DOCKING

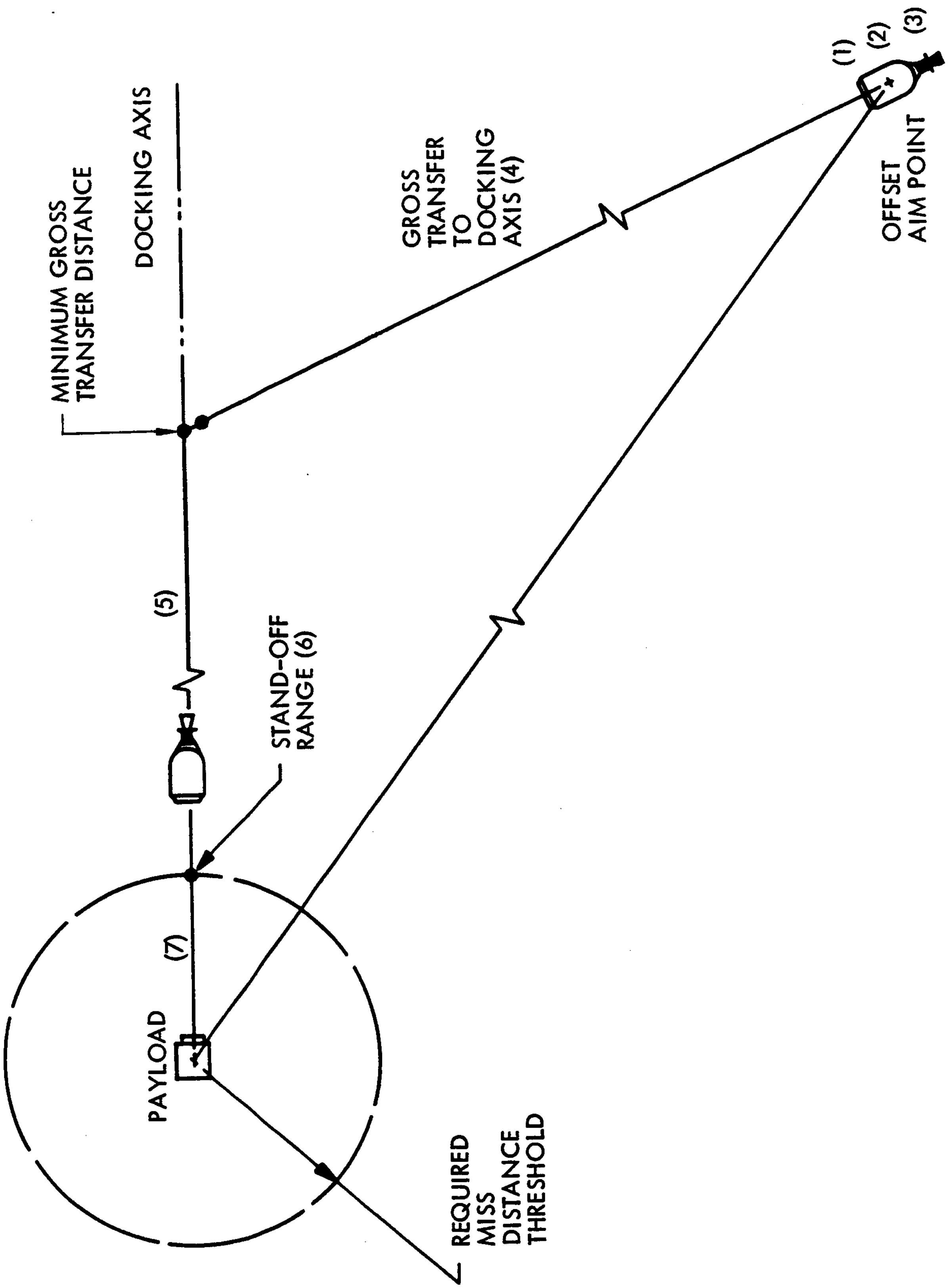

Fig. 4-2 Autonomous Docking Phases

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:

$$\text{Aim Point (AP), (nm)/RM} = \left\{ PU^2 + GAP_1^2 + \left[\frac{GAV_1}{6076} (SFT + DTI) \right]^2 + DA^2 \right\}^{1/2}$$

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 GAP_1 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 = mass of vehicle (slugs), kg

T = Thrust (lb_f), n

The acquisition range (ACQ) then is:

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

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 $\pm 1.57 \times \pm 1.57$ 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 $\pm .96 \times \pm .96$ rad ($\pm 55^\circ \times \pm 55^\circ$) (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:

$$V_{rel} = 6.04 \text{ m/sec } (19.8 \text{ ft/sec})$$

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:

$$SFT = \frac{\text{initial range} \times \tan(.1 \text{ FOV})}{V_{rel}}$$

Thus for $\pm 0.96 \times \pm 0.96$ rad ($\pm 55^\circ \times 55^\circ$) FOV:

$$SFT = \frac{(821) \times (.19438)}{19.8} = 8.06 \text{ sec}$$

5.5 RANGE, ELEVATION AND AZIMUTH ACCURACY

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

Range:	.1% of range
Angle:	0.0008725 rad (.05°)

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:

Resolution:	Range	.09 m, (0.3 ft)
	Angle	.0436 m rad (0.0025 deg.)
Bias:	Range	.0046 m (0.015 ft)
	Angle	.0034 rad (0.0002 deg.)

5.7 ACQUISITION AND TRACKING RATES

The following minimum rates are suggested:

Acquisition:	0.0279 rad/sec (1.6°/sec)
Tracking:	0.0506 rad/sec (2.9°/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 object in the FOV after discrimination.

The sensor should be able to operate if the sun, moon, or earth limbs are more than 0.08725 rad (5^{o}) 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 minimum of 16 range, azimuth, and elevation measurements per second is adequate.

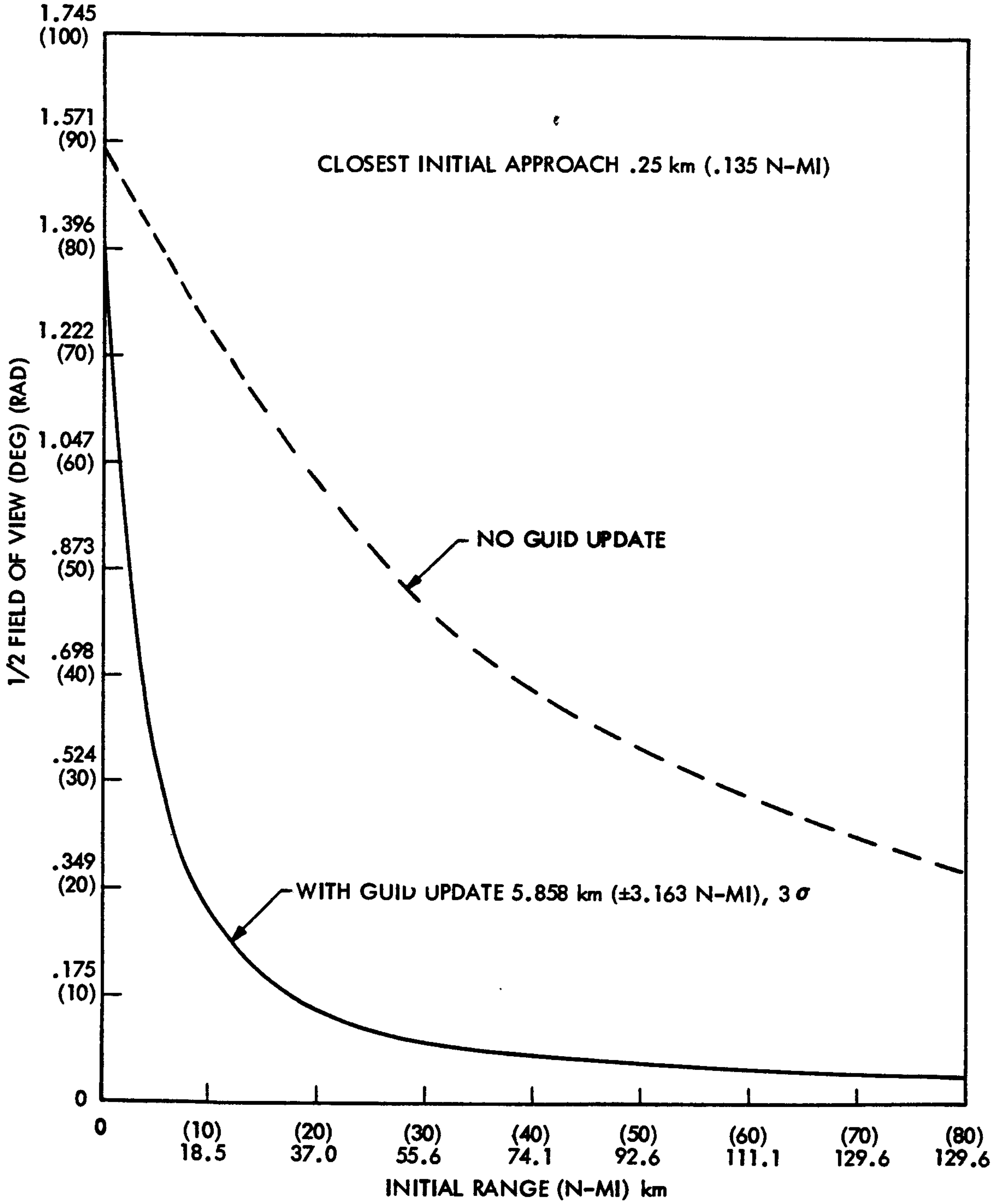

FIG. 5-1 SENSOR FIELD OF VIEW REQUIREMENTS

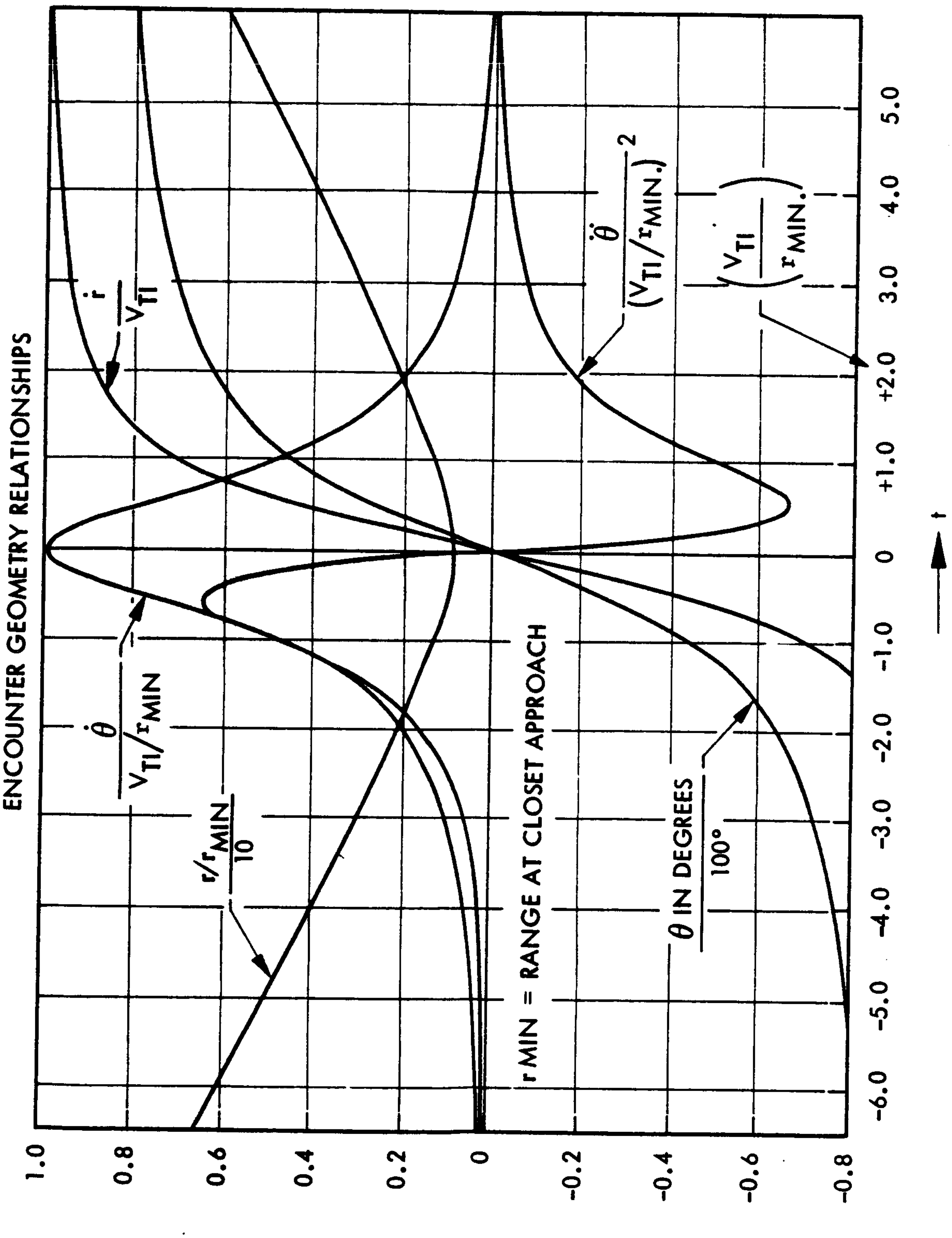

Fig. 5-2 Encounter Relationships

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.

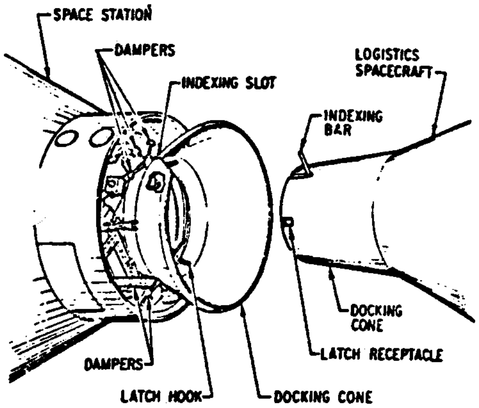

Fig. 6-1 Gemini Docking System

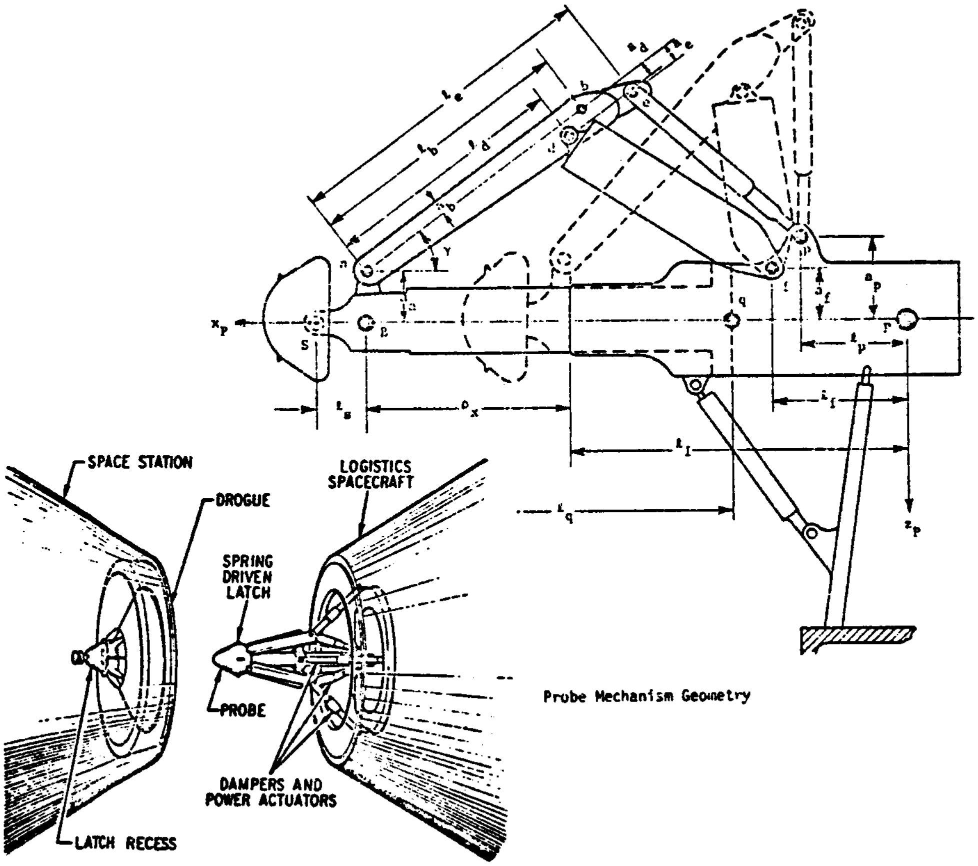

Fig. 6-2 Apollo Docking System

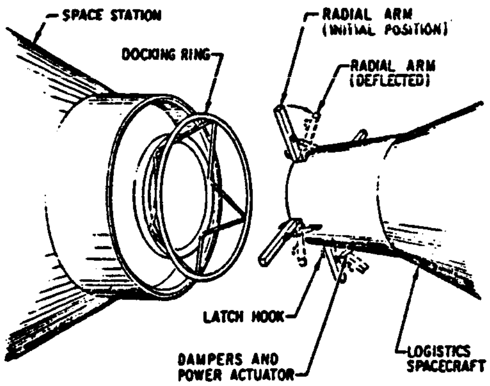

Fig. 6-3 Menasco Docking System

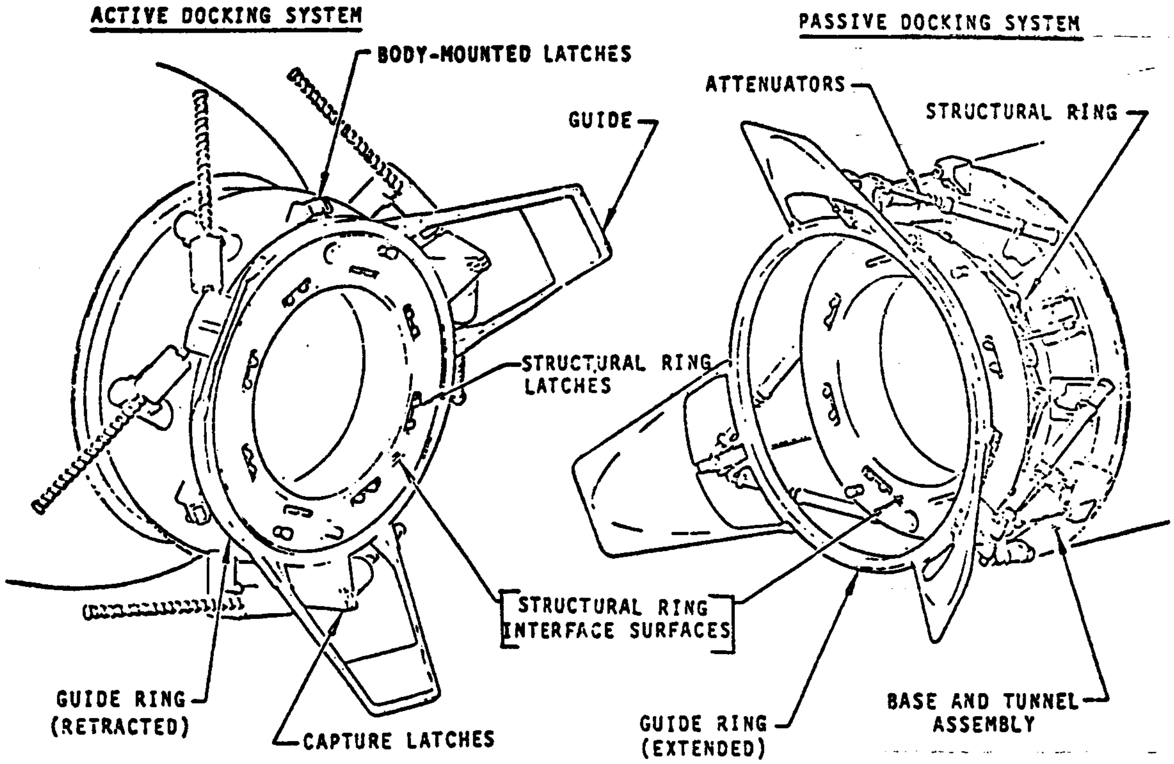

Fig. 6-4 International Docking System

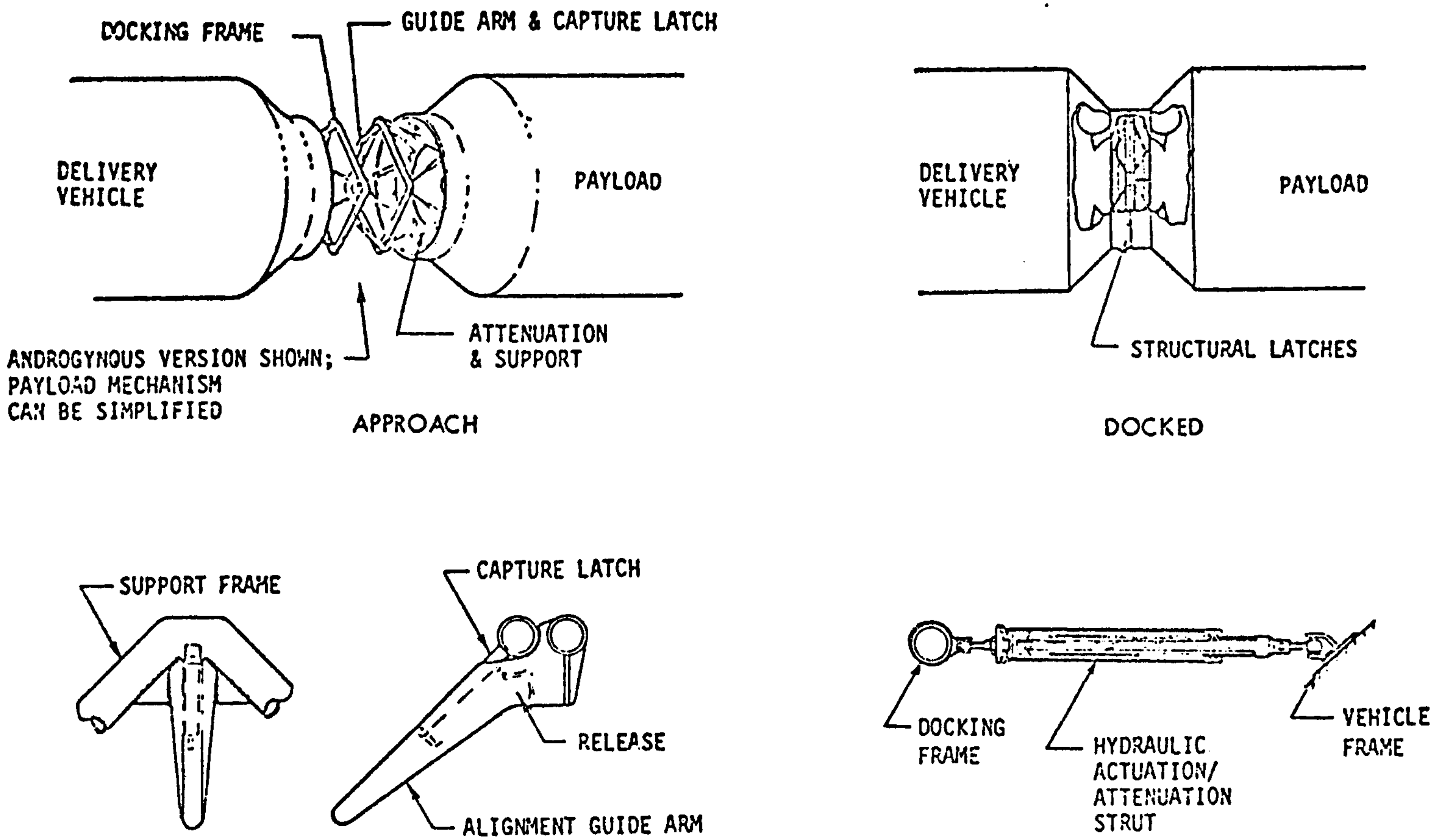

Fig. 6-5 Square Frame Docking System

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 panesl 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 6-1

Requirements	Gemini	Apollo	Menasco	International	Square Frame
1	3	3	3	3	3
2	3	3	1	2	3
3	3	2	1	2	1
5	0	3	3	3	3
6	3	3	3	3	3
7	3	1	3	3	3
8	3	3	3	3	2
9	2	1	3	3	3
10	3	3	3	3	2
12	3	0	0	2	2
TOTAL	26	22	23	27	25

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

DOCKING ACCURACY STRUCTURAL SPECIFICATIONS

	Units	Gemini Ref. 18	Apollo Ref. 7	Baseline Space Tug Ref. 22
Centerline Miss Distance	(ft) m	(0 to 1.0) 0 to .3048	(0 to 1.0) 0 to .3048	(0 to 1.0) 0 to .3048
Miss Angle	(deg) rad	(0 to 10.0) 0 to .1745	(0 to 10.0) 0 to .1745	(0 to 5.0) 0 to .08725
Longitudinal Velocity	(ft/sec) m/sec	(1.5 max)	(0.1 to 1.0)	(0.1 to 1.0)
Lateral Velocity	(ft/sec) m/sec	(0 to 0.5)	(0 to 0.5)	(0 to 0.30)
Angular Velocity in	(deg/sec)			
Pitch,	rad/sec	(0 to 0.75) 0 to .01309		
Yaw,		(0 to 0.75) 0 to .01309		
Roll,		(0 to 10.0) 0 to .1745		
Combined		0 to .1745	(0 to 1.0) 0 to .0175	(0 to 0.50) 0 to .008725

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 center line 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 LB_f-sec) for 15.24 cm to 4092 N-sec (920 LB_f-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 consistant with the docking mechanism optimization.

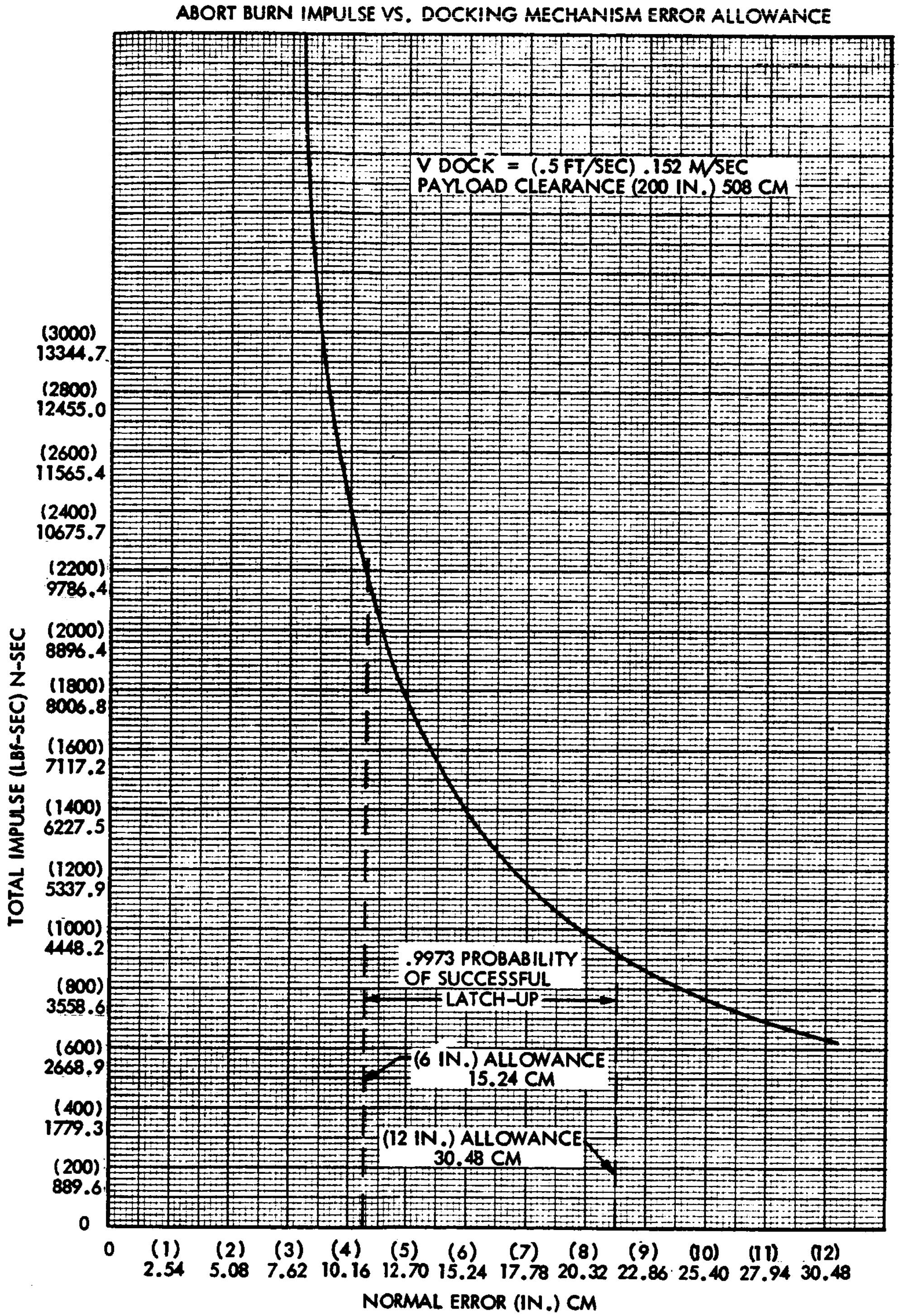

Figure 6-6

ABORT BURN IMPULSE VS. DOCKING MECHANISM ERROR ALLOWANCE

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

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away from the Tug is 171.3 newton (38.5 lb_f) 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 netwons (0.094 lb_f) 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 studies, 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-lb_f) 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 lb_f-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-lb_f); 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 LOCDOK is:

$$I_T = 2I_{TA} + I_{TOD} + \text{MASS}\left(2\left(V_{RY} + V_{OD}\right) + V_{Retro}\right) \qquad (7.1)$$

$$I_{TA} = 50\left[\frac{2\ Ra}{VDOCK} - \sqrt{\left(\frac{2\ Ra}{VDOCK}\right)^2 - \frac{8\ (Yc + 7.33)}{a}}\right] \qquad (7.2)$$

$$V_{Retro} = \frac{\left(R_{2\ min} + 23.3 + P_w\right)}{t_I} \tag{7.3}$$

$$V_{Ry} = \frac{Yc + Y_{safety}}{t_I} \tag{7.4}$$

where:

I_t = Total impulse required for abort and redocking

Ra = Standoff point distance

Yc = Clearance required below docking mechanism axis

Y_{safety} = Clearance below Yc required for antenna, etc.

a = Acceleration of Tug thrust/vehicle mass

V_{dock} = Docking velocity

$R_{2\ min}$ = Distance from payload on the docking axis to start final docking approach

t_I = time allocated to return to $R_{2\ min}$ from below payload after abort

P_w = Payload width

V_{Ry} = Velocity along the Y-axis

I_{TOD} = Total impulse required to reach the SOP from R_2 min

I_{TA} = Initial abort burn total impulse

V_{Retro} = Velocity along the docking axis required to reach $R_{2\ min}$ after abort

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} = .152 m/sec (.5 ft/sec)

I_{TOD} = 66723.3 N-sec (15,000 lb_f-sec) from LOCDOK simulation

P_w = 10.16 m (33.34 ft)

$R_{2\ min}$ = 304.8 (1000 ft)

Y_{safety} = 22.63 m (74.25 ft)

t_I = 3600 sec

MASS = 14593.9 kg (1000 slugs)

From Equation 7.1

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

$$I_t = 2160 + 15000 + 1399.5$$

$$I_t = (18559.5\ lb_f\text{-sec})\ \ 82556.7\ \text{N-sec}$$

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 $R_{2\ min}$ the least. Note, however, from Equation 7.3 that this impulse is inversely proportional to the time allotted in arriving at $R_{2\ min}$ 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:

$$t_A = t_C + t_{CB} + t_I + t_{VOD} + t_{OD} \tag{7.5}$$

$$t_C = Ra/VDOCK \tag{7.6}$$

$$t_{CB} = \frac{P_w + 23.3 + \dfrac{V_{DOCK}^2 + V_{Retro}^2}{2a}}{V_{DOCK}} \tag{7.7}$$

$$t_{VOD} = V_{OD}/a \tag{7.8}$$

$$t_{OD} = R_{2\ min}/VOD \tag{7.9}$$

where:

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

From Equation 7.5:

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

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

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 .152 m/sec (.5 ft/sec) to save the total impulse required to accelerate to VOD and deaccelerate to VDOCK.

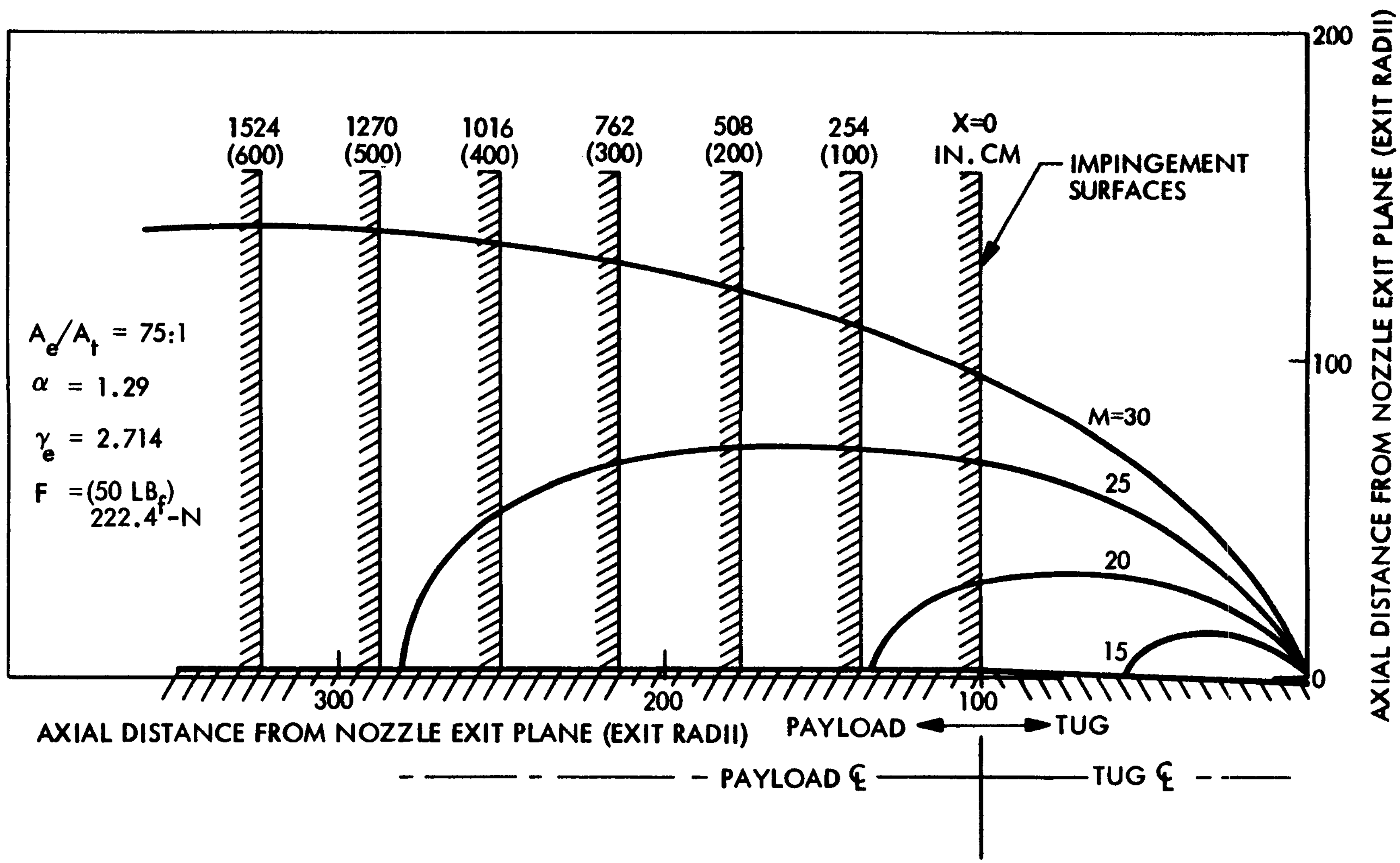

Fig. 7-1 Forward Thruster Impingement

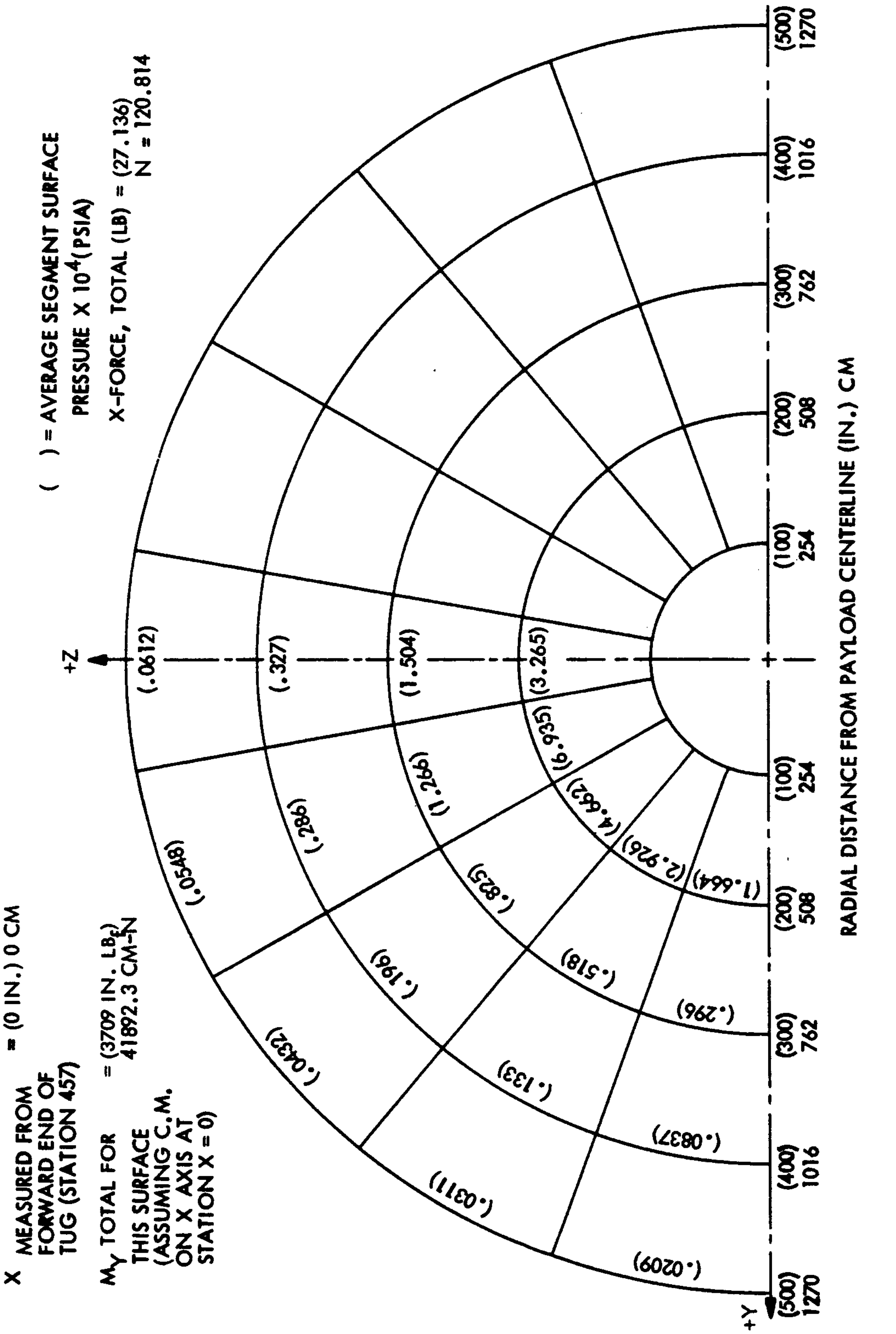

FIG. 7-2 FORWARD THRUSTER IMPINGEMENT 0. CM SEPARATION

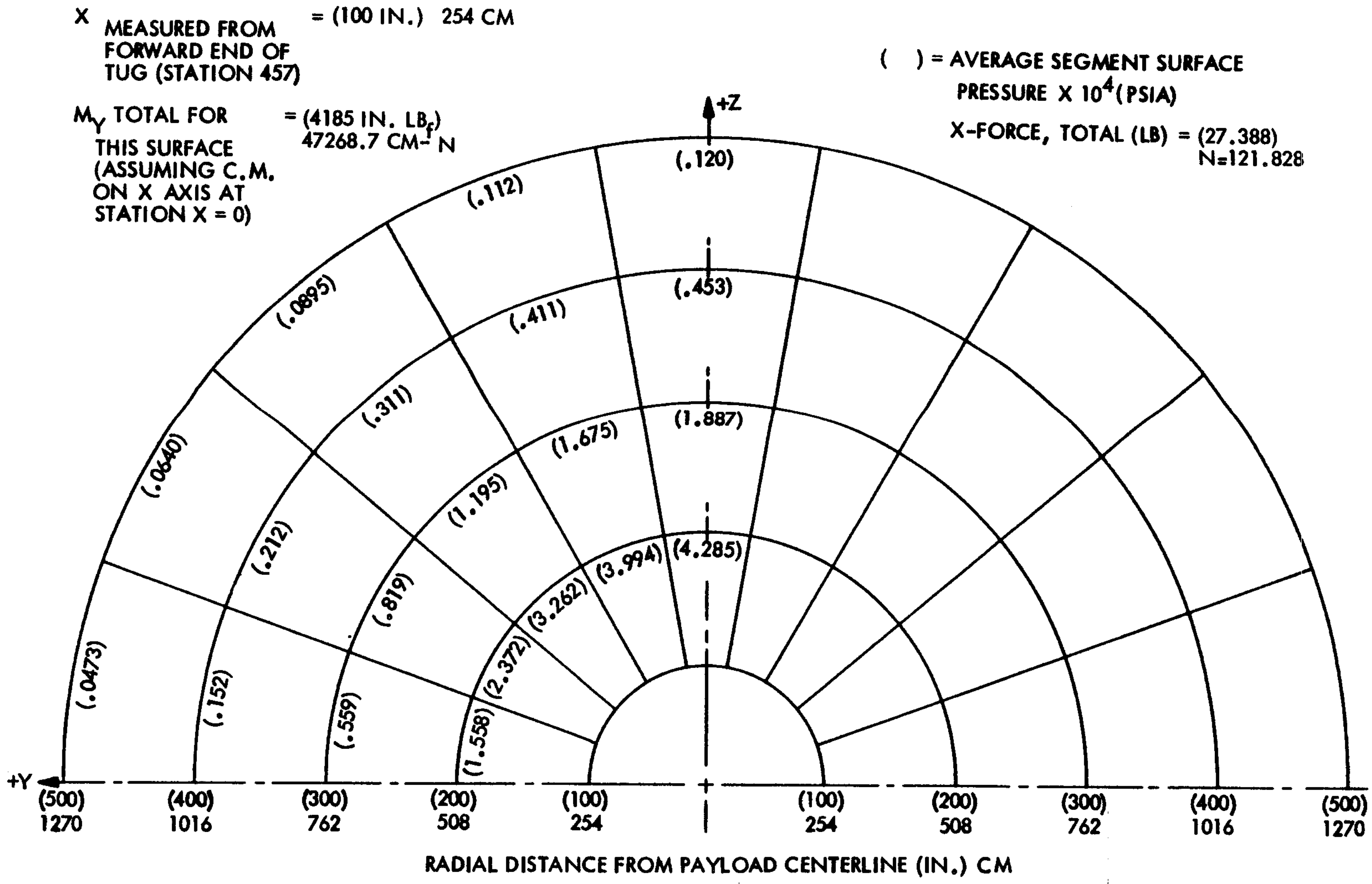

FIG. 7-3 FORWARD THRUSTER IMPINGEMENT 254 CM SEPARATION

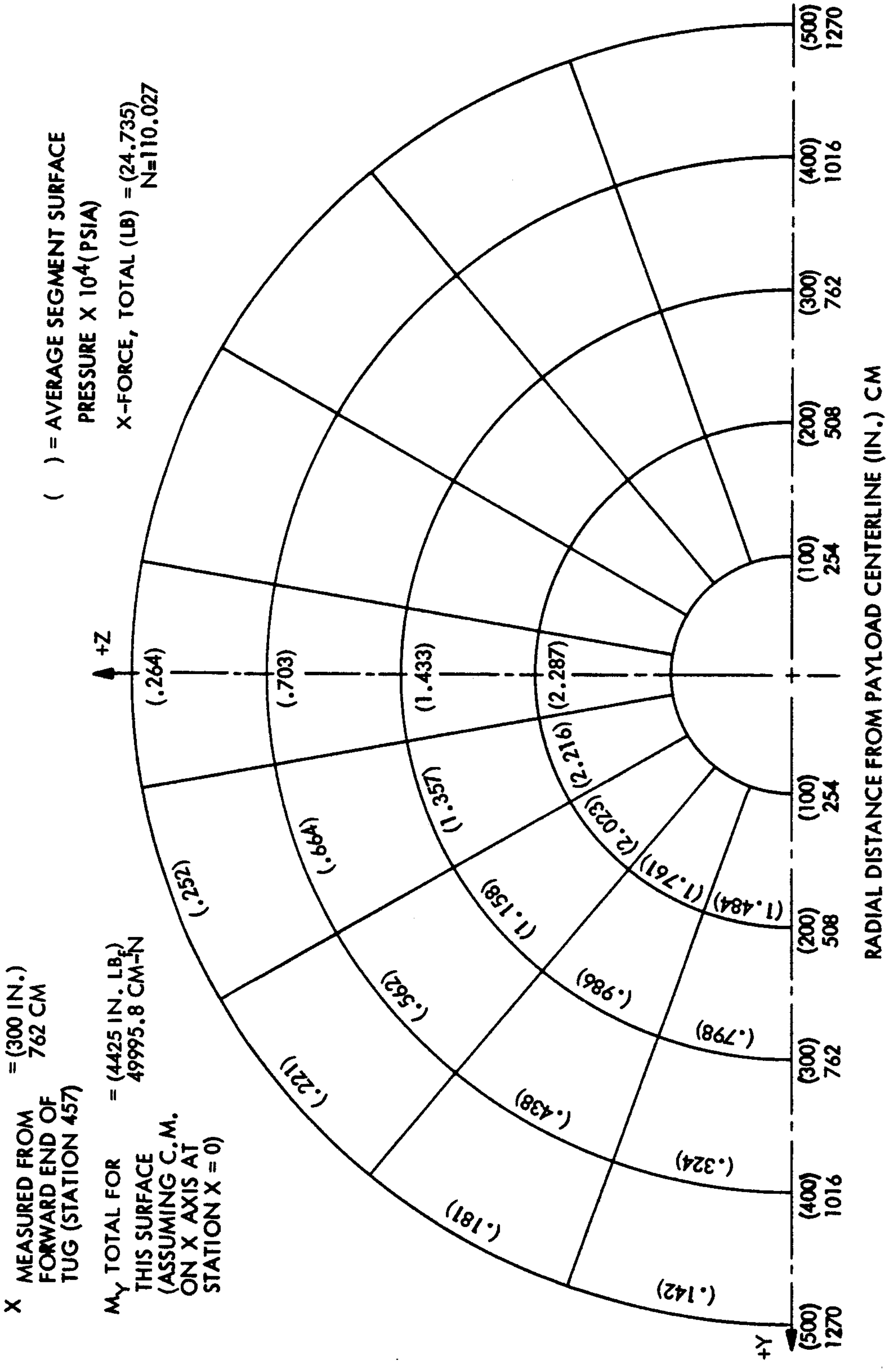

FIG. 7-4 FORWARD THRUSTER IMPINGEMENT 508 CM SEPARATION

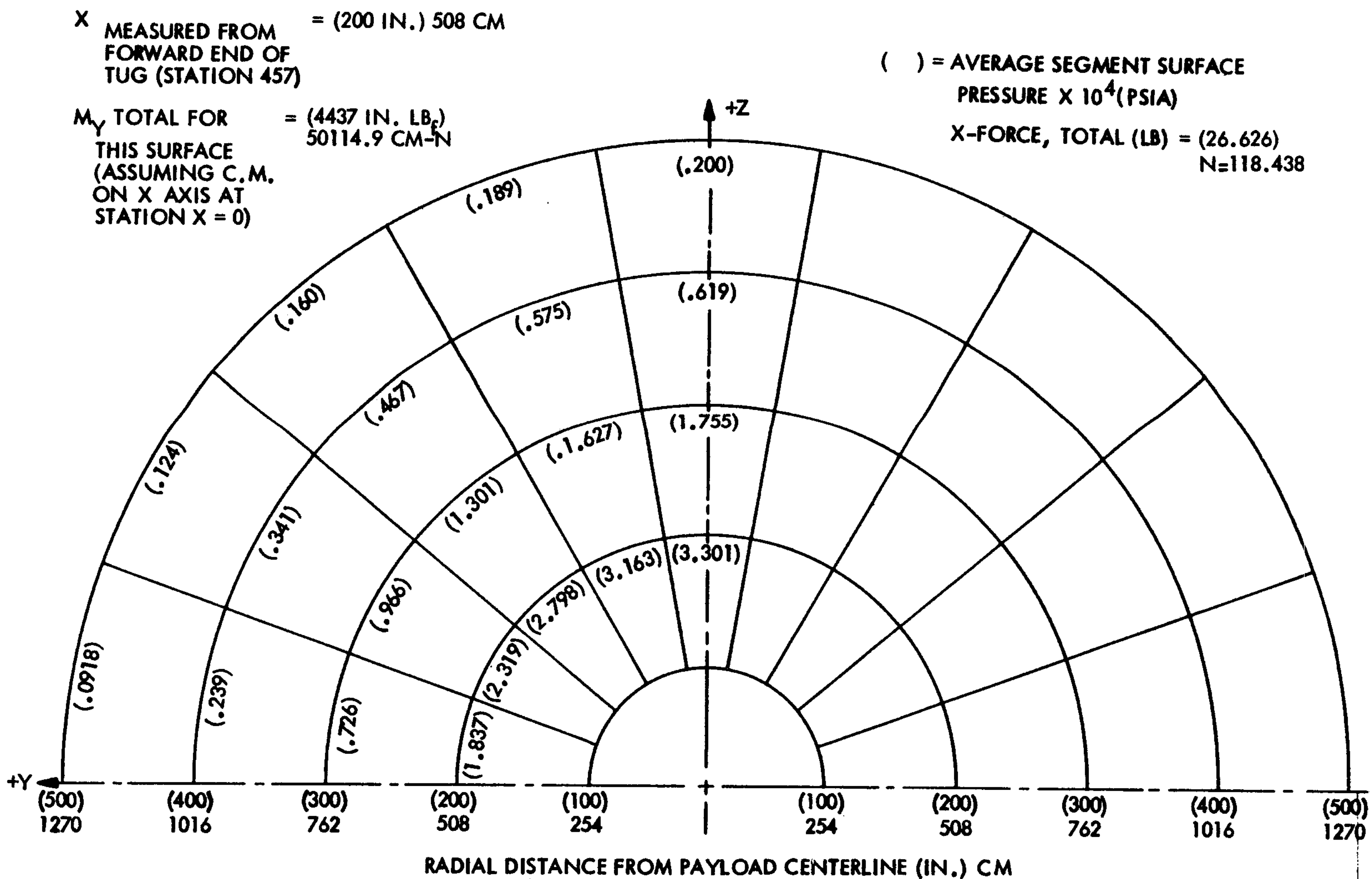

FIG. 7-5 FORWARD THRUSTER IMPINGEMENT 762 CM SEPARATION

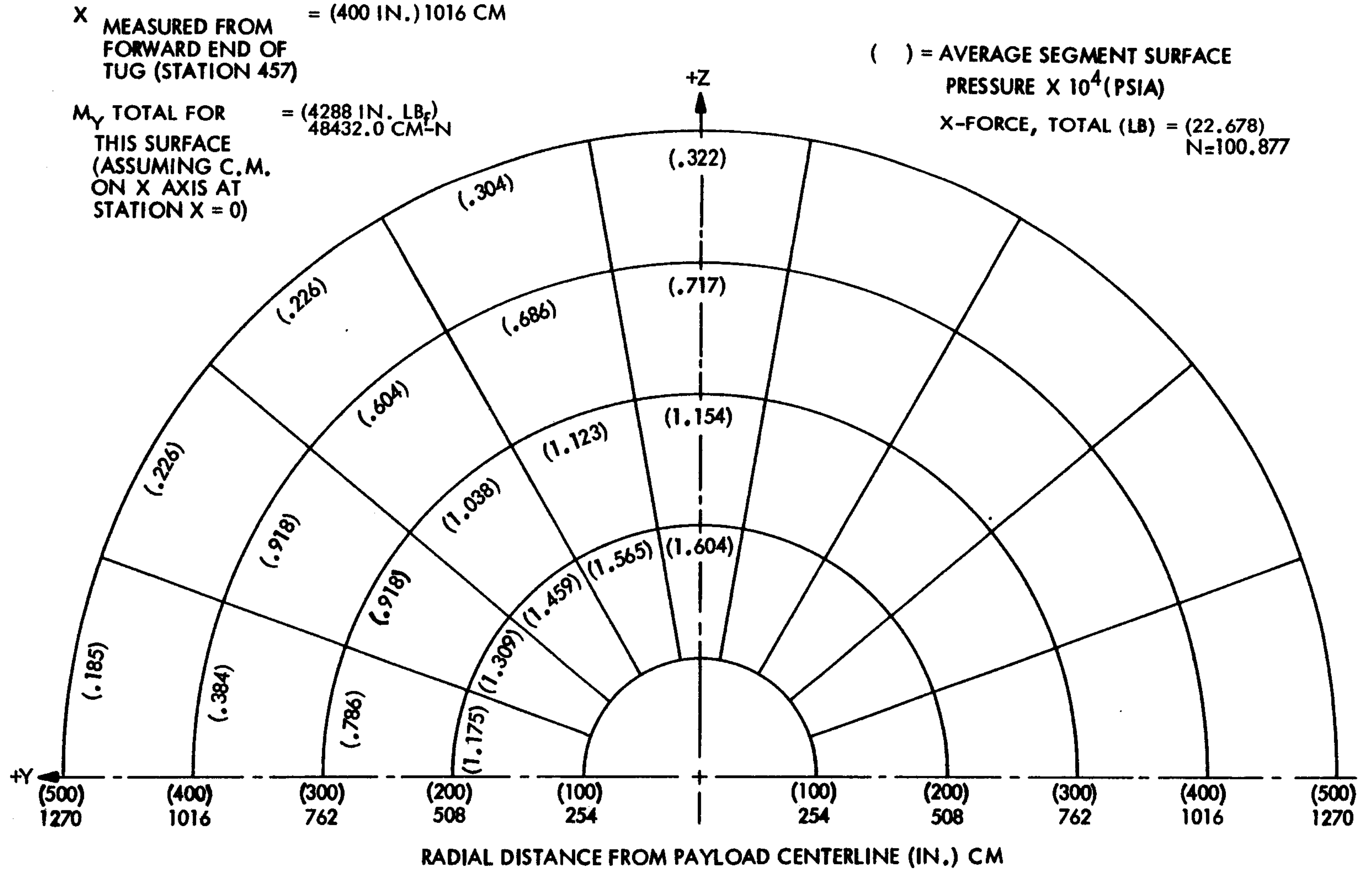

FIG. 7-6 FORWARD THRUSTER IMPINGEMENT 1016 CM SEPARATION

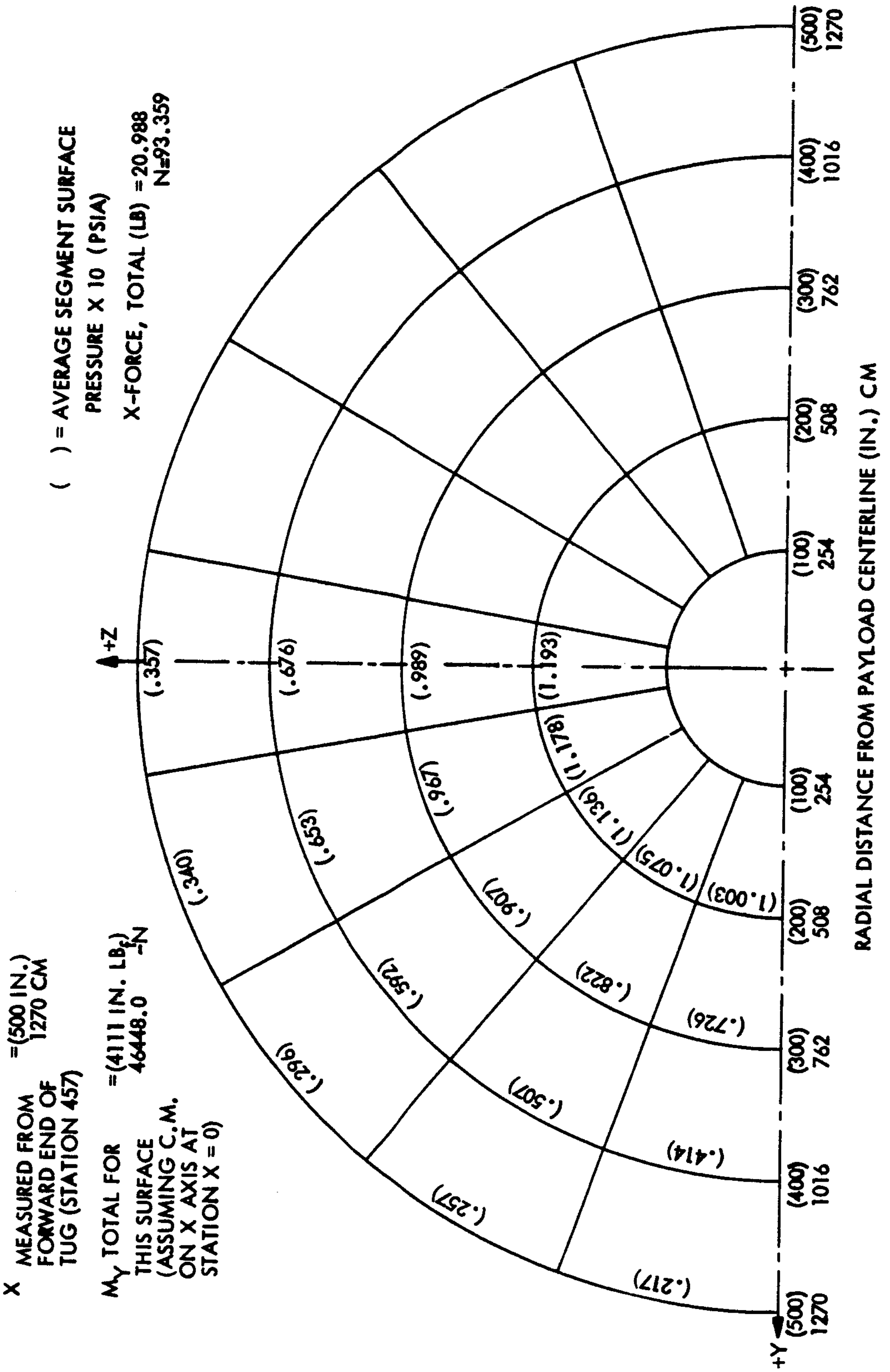

FIG. 7-7 FORWARD THRUSTER IMPINGEMENT 1270 CM SEPARATION

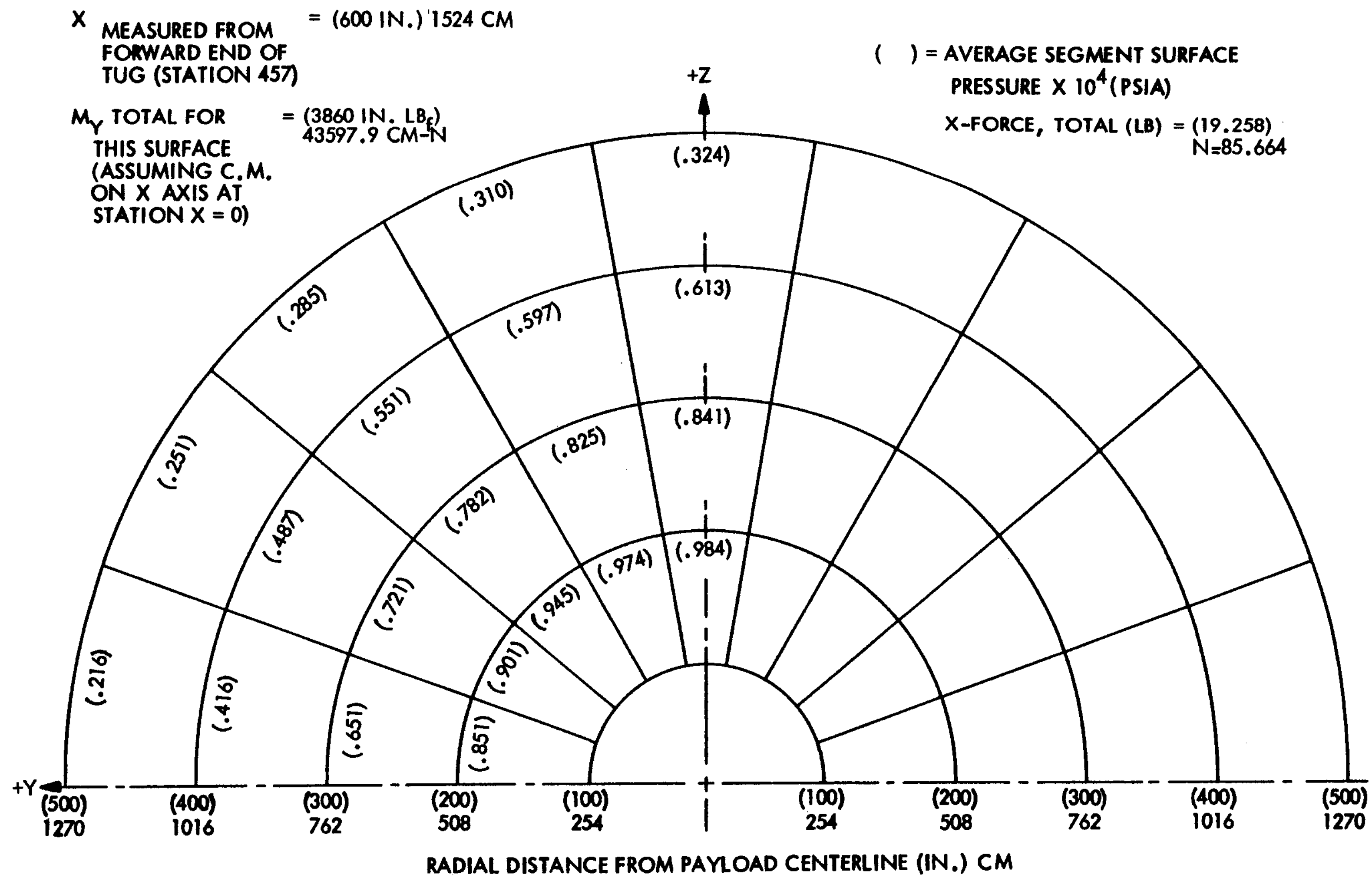

FIG. 7-8 FORWARD THRUSTER IMPINGEMENT 1524 CM SEPARATION

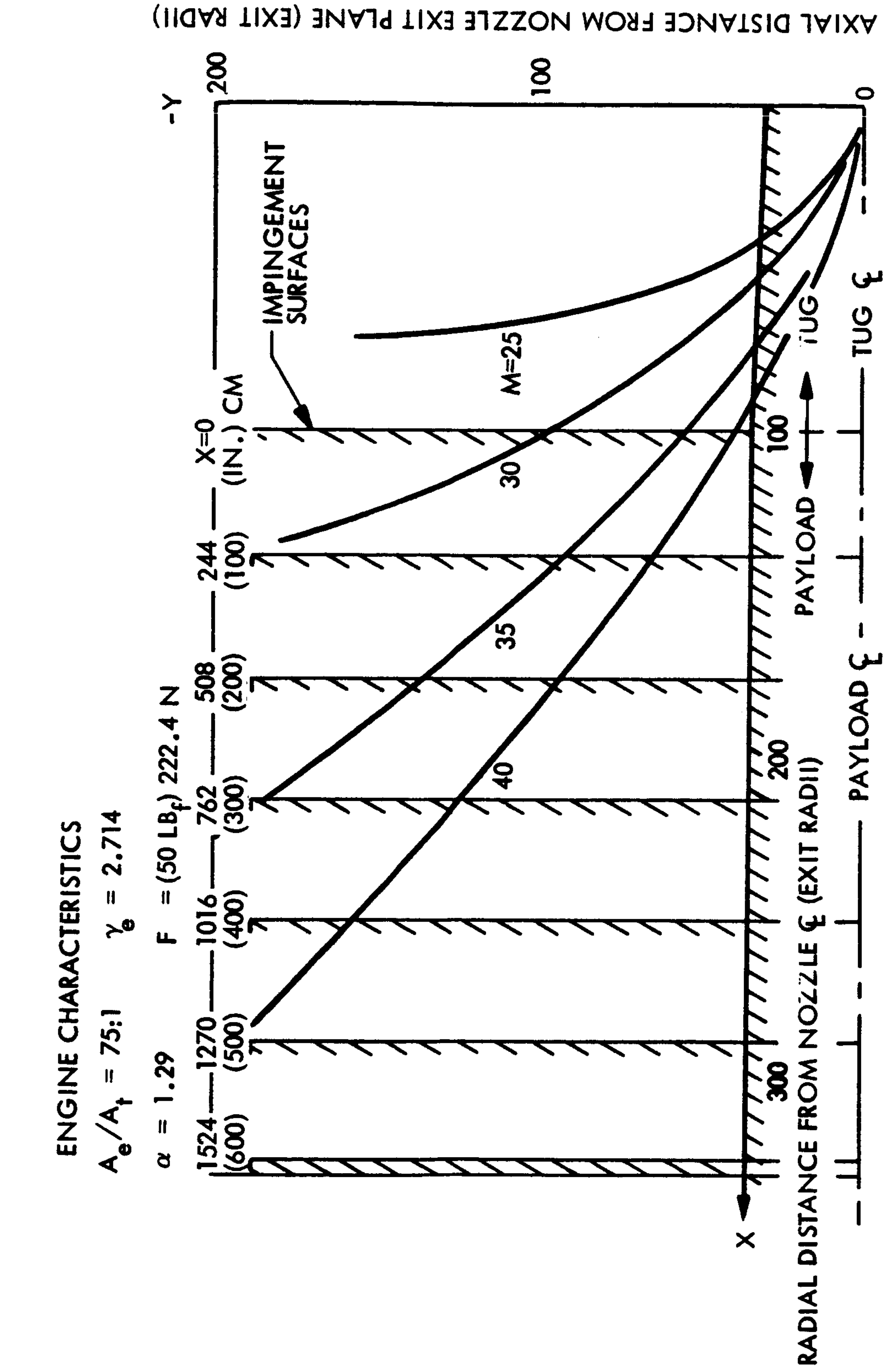

Fig. 7- Normal Thruster Impingement

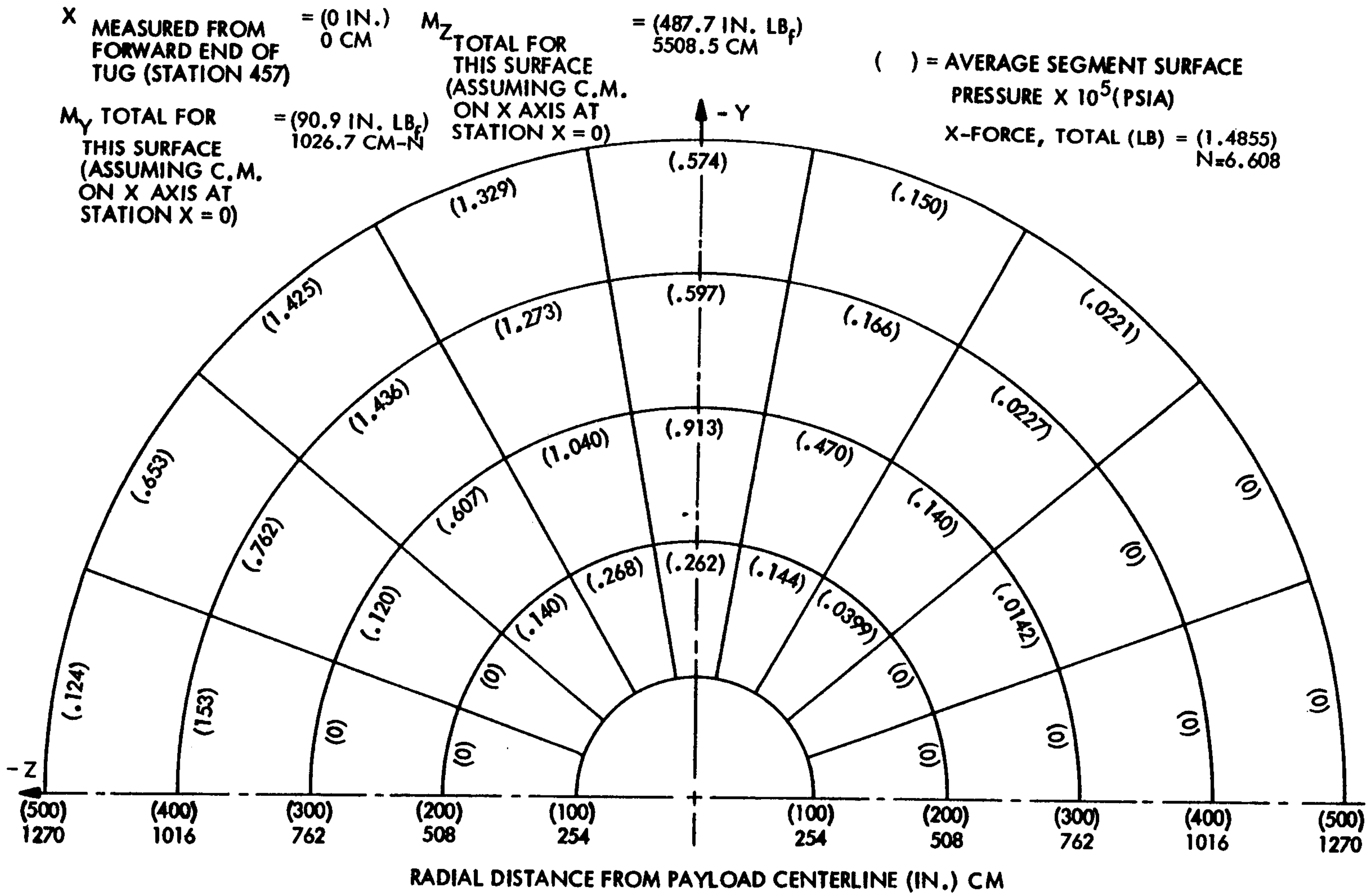

FIG. 7-10 NORMAL THRUSTER IMPINGEMENT 0. CM SEPARATION

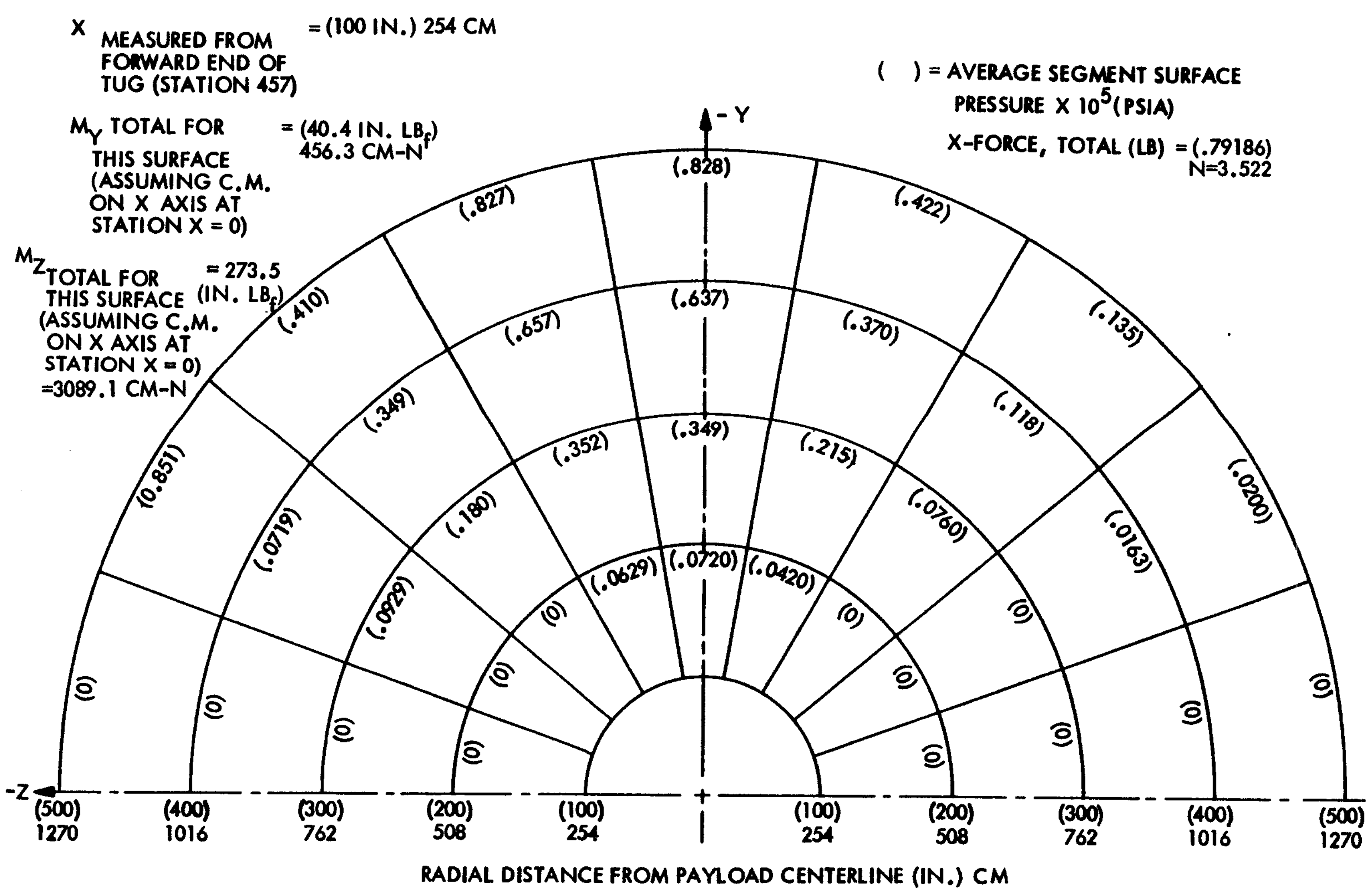

FIG. 7-11 NORMAL THRUSTER IMPINGEMENT 254 CM SEPARATION

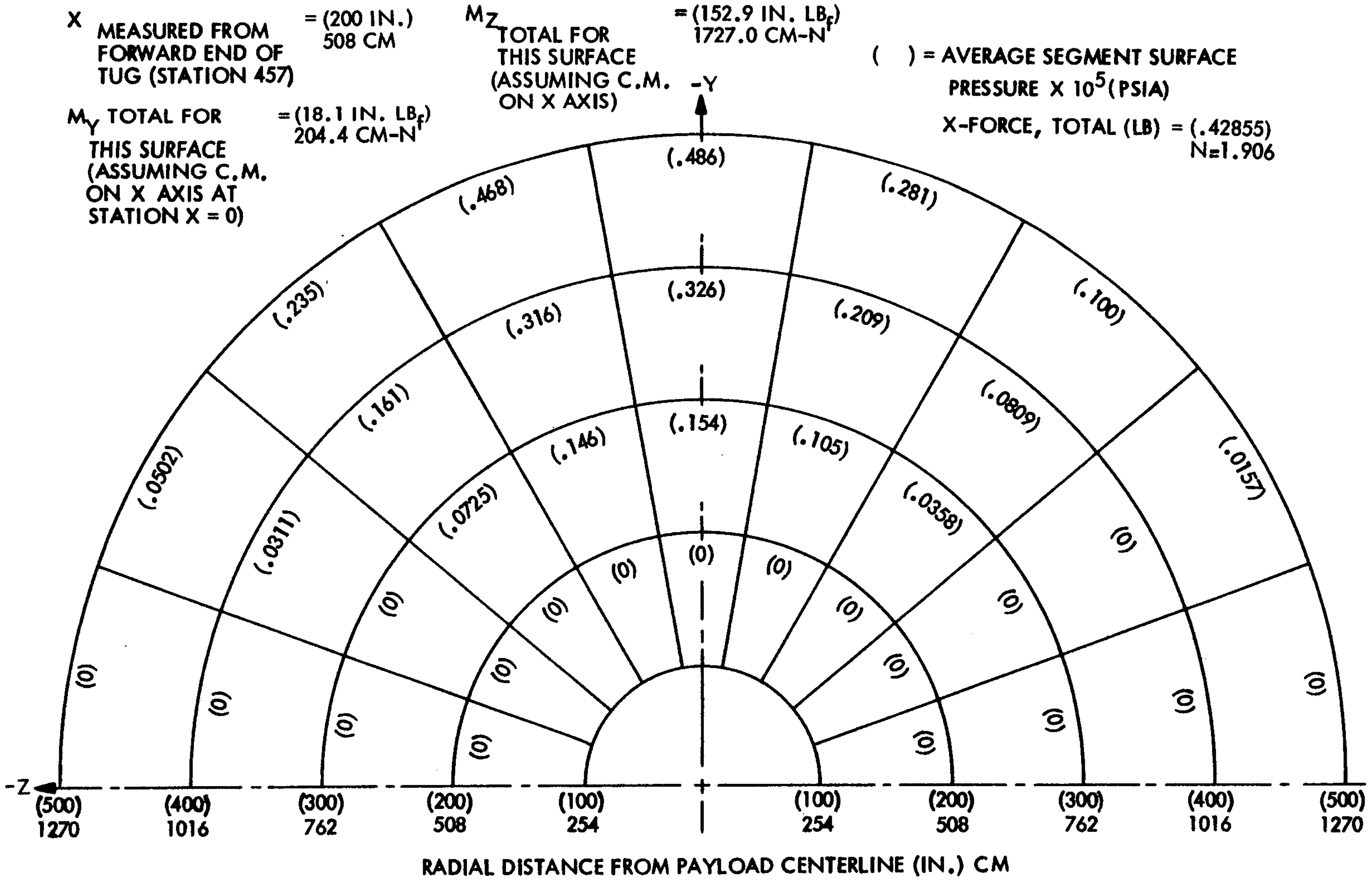

FIG. 7-12 NORMAL THRUSTER IMPINGEMENT 508 CM SEPARATION

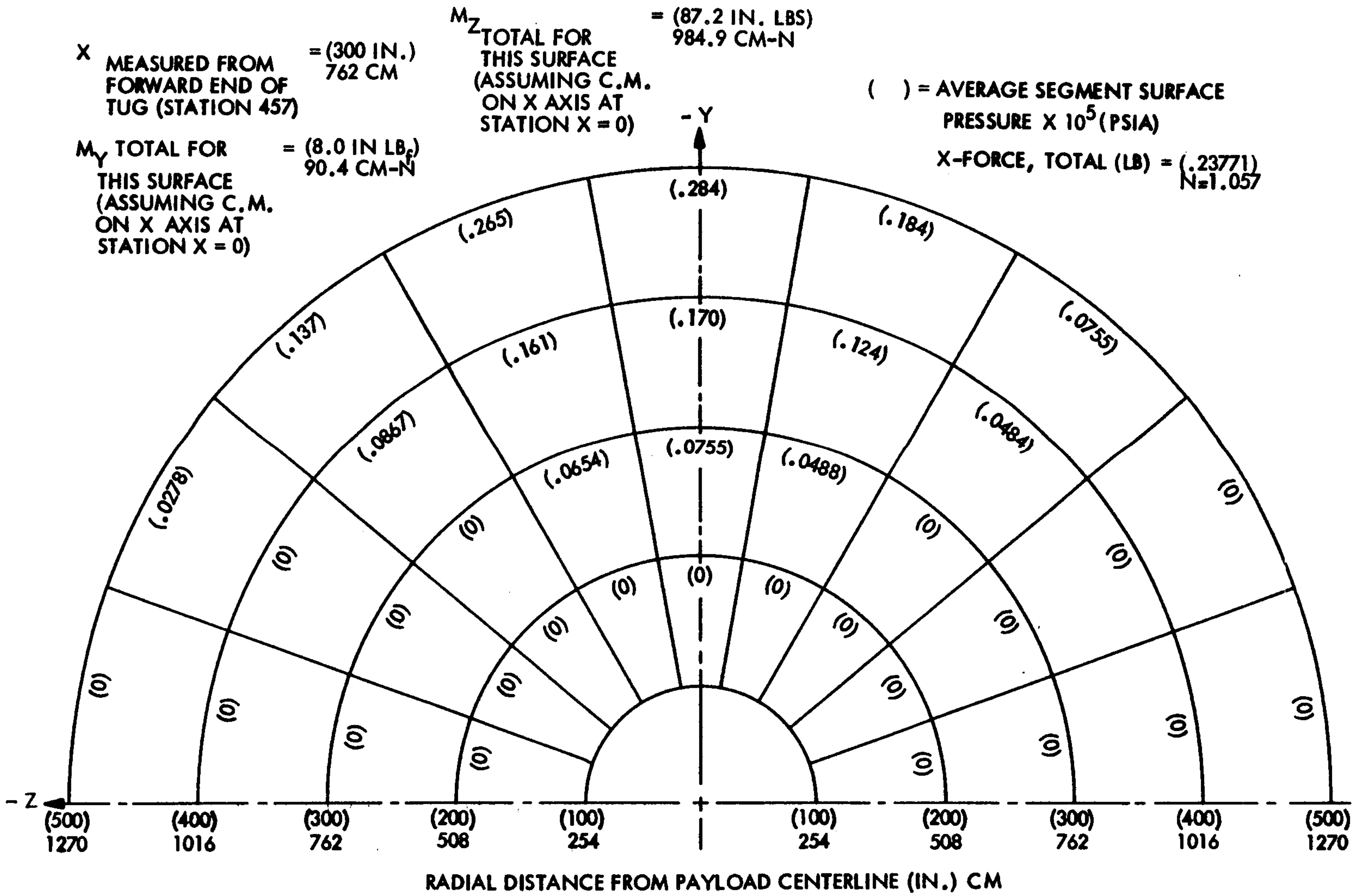

FIG. 7-13 NORMAL THRUSTER IMPINGEMENT 762 CM SEPARATION

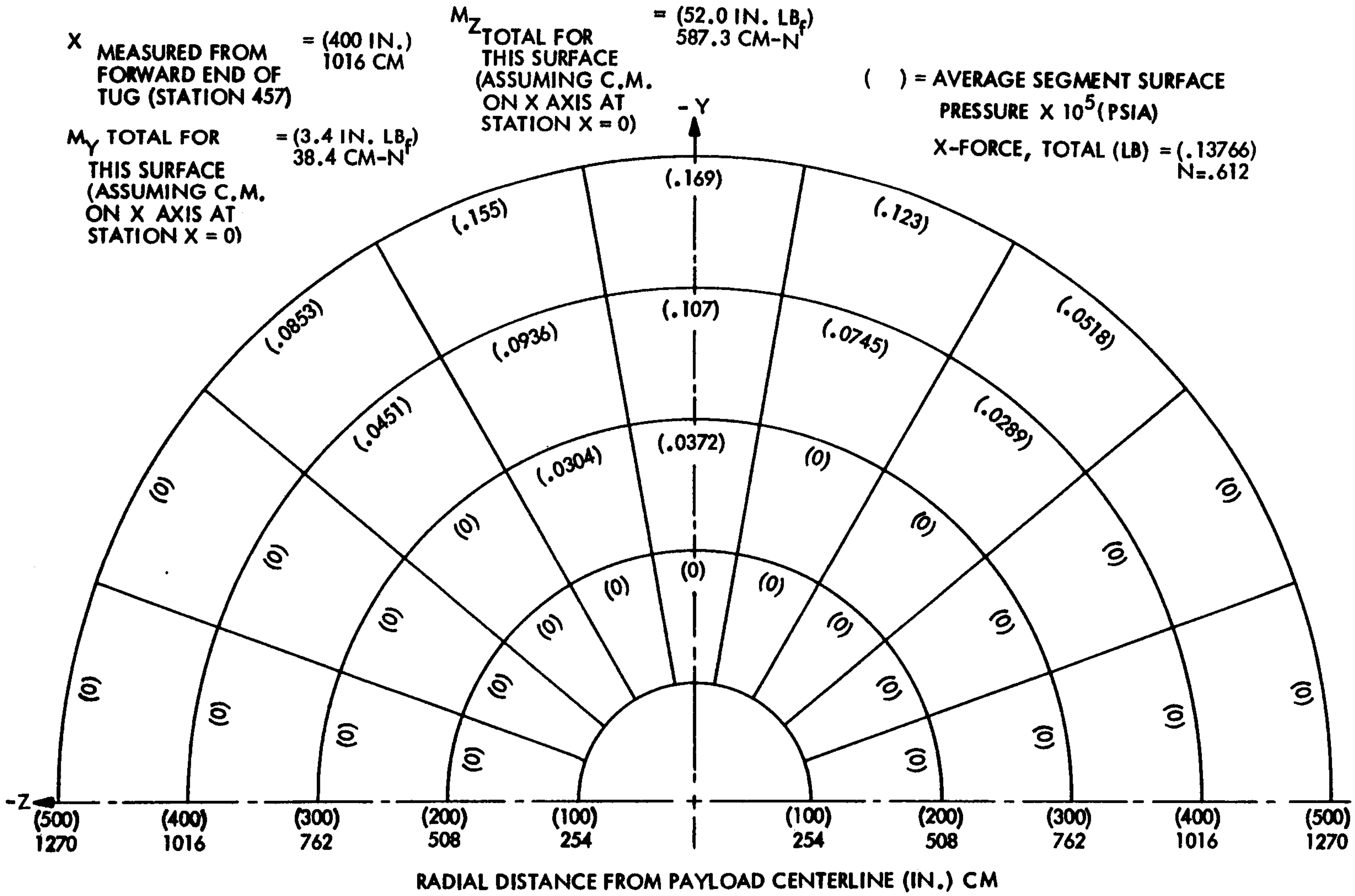

FIG. 7-14 NORMAL THRUSTER IMPINGEMENT 1016 CM SEPARATION

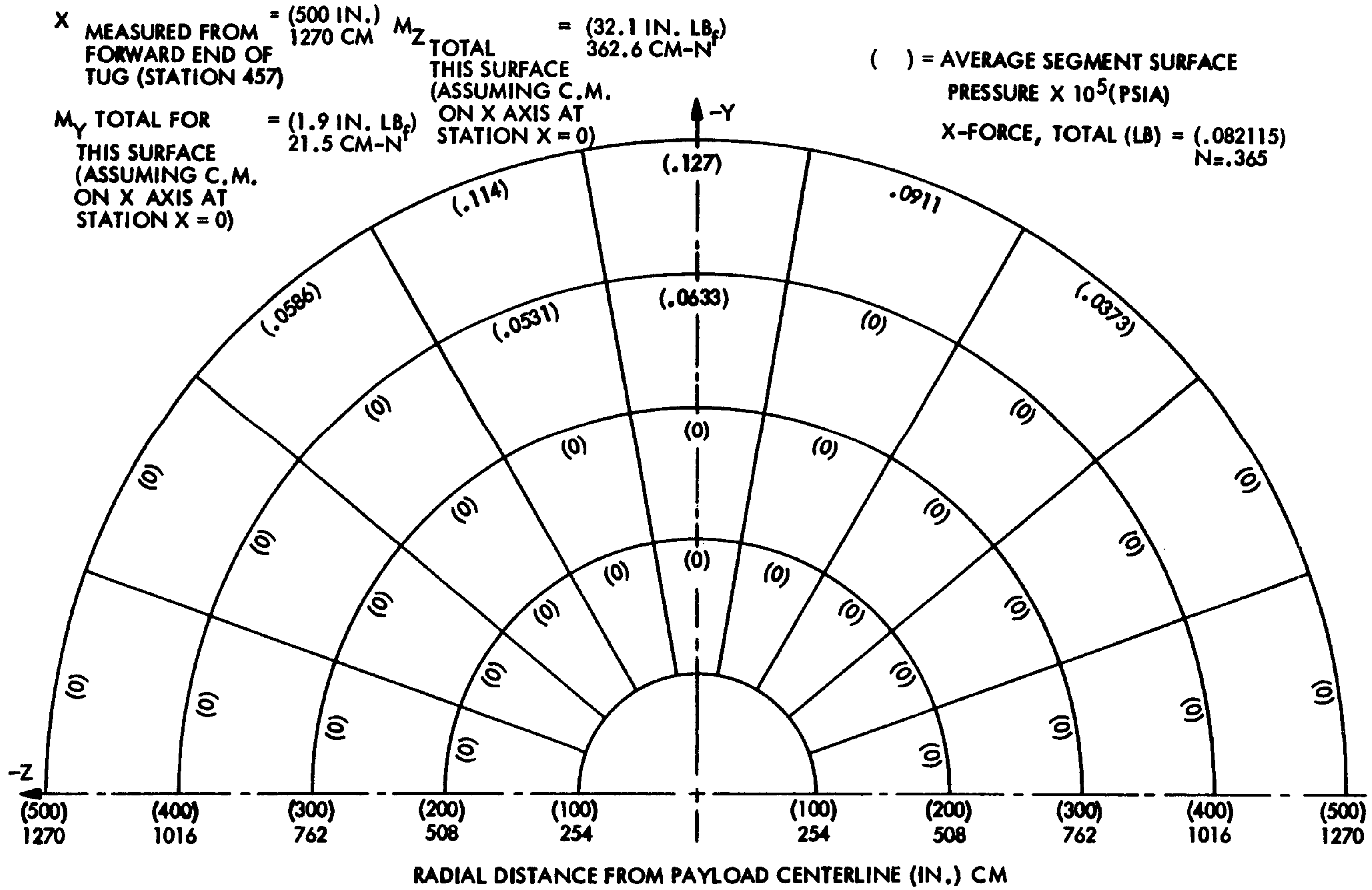

FIG. 7-15 NORMAL THRUSTER IMPINGEMENT 1270 CM SEPARATION

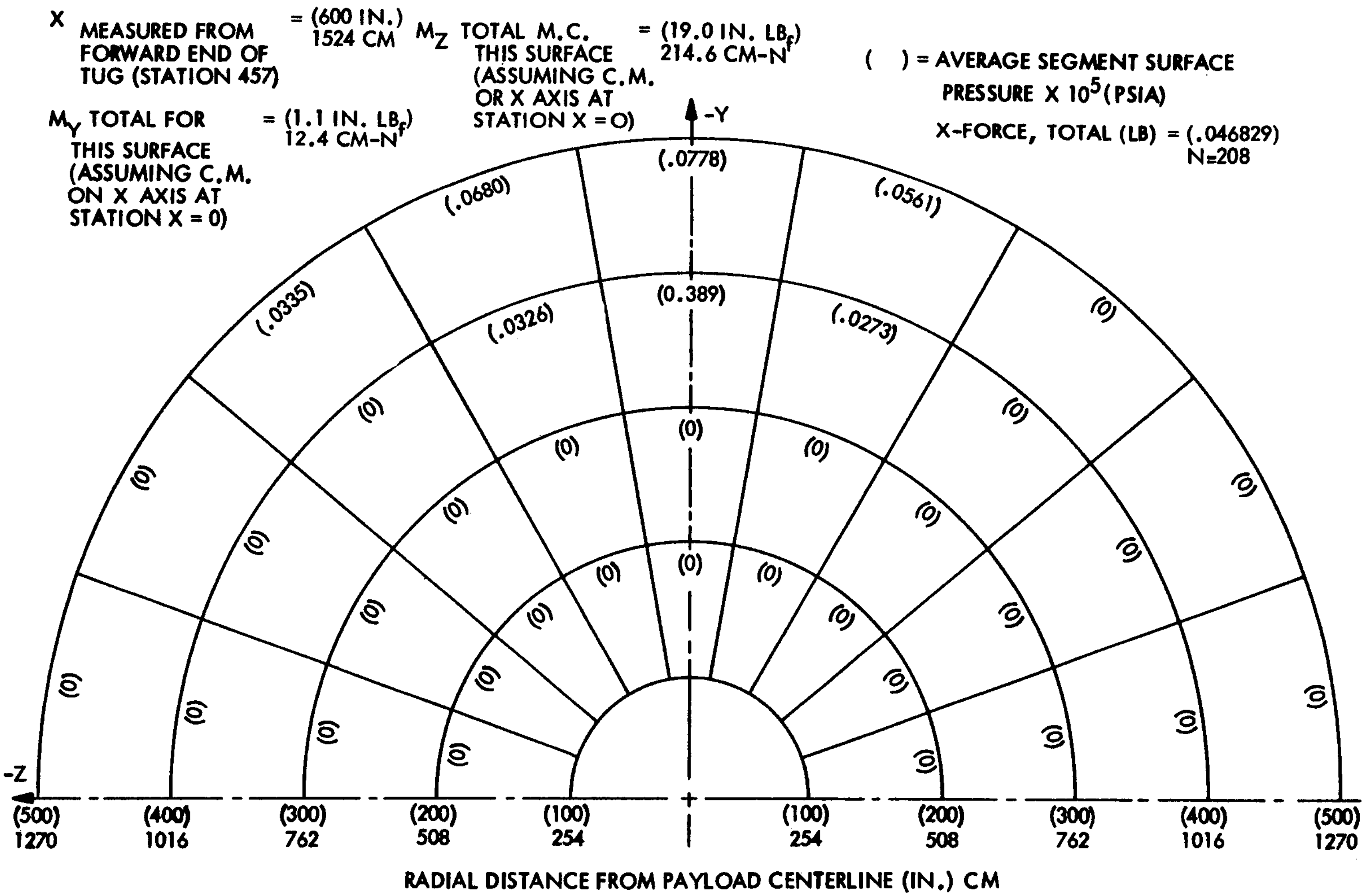

FIG. 7-16 NORMAL THRUSTER IMPINGEMENT 152X CM SEPARATION

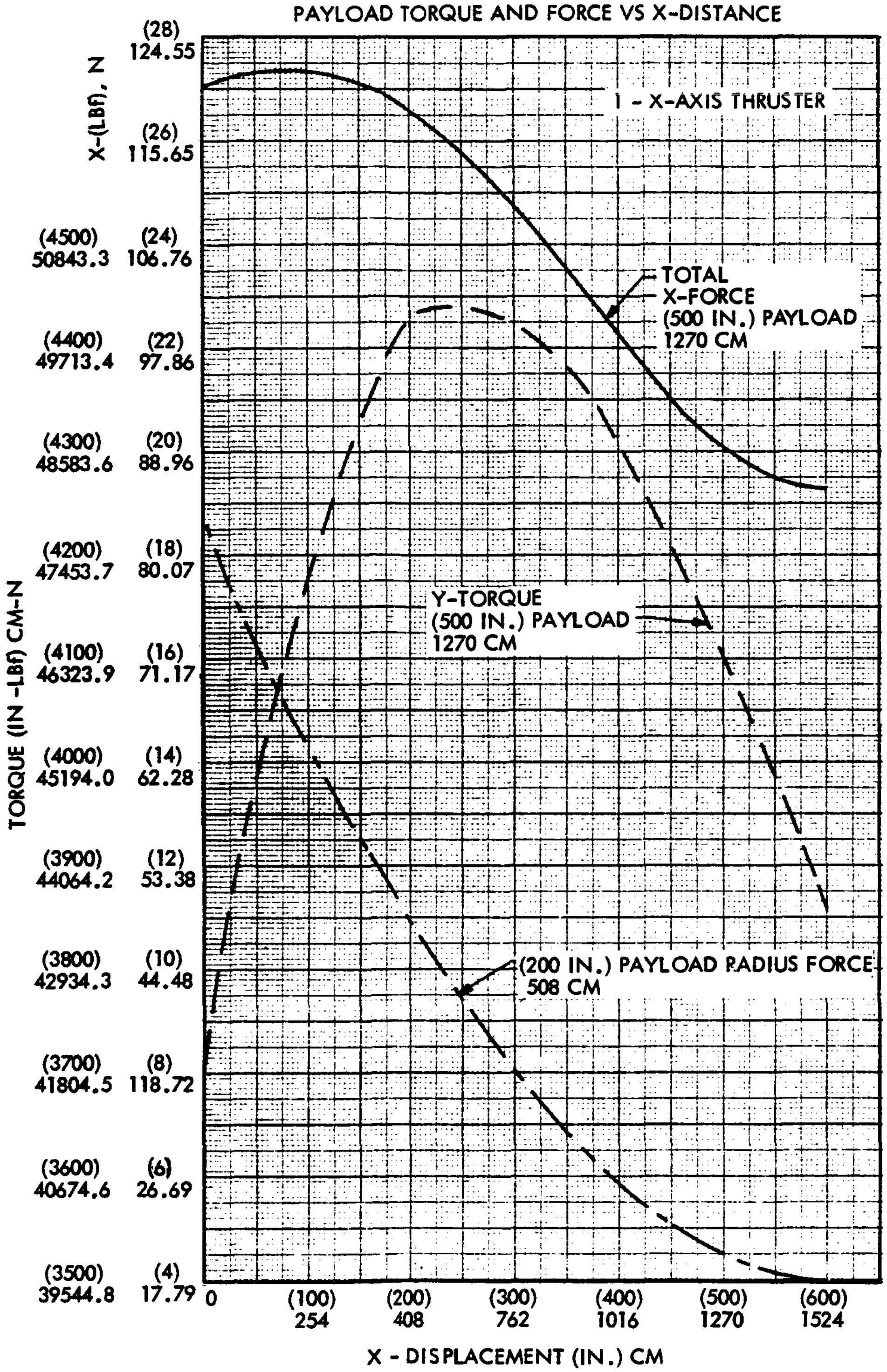

FIG. 7-17 PAYLOAD TORQUE AND FORCE VS
X-DISTANCE FORWARD THRUSTER

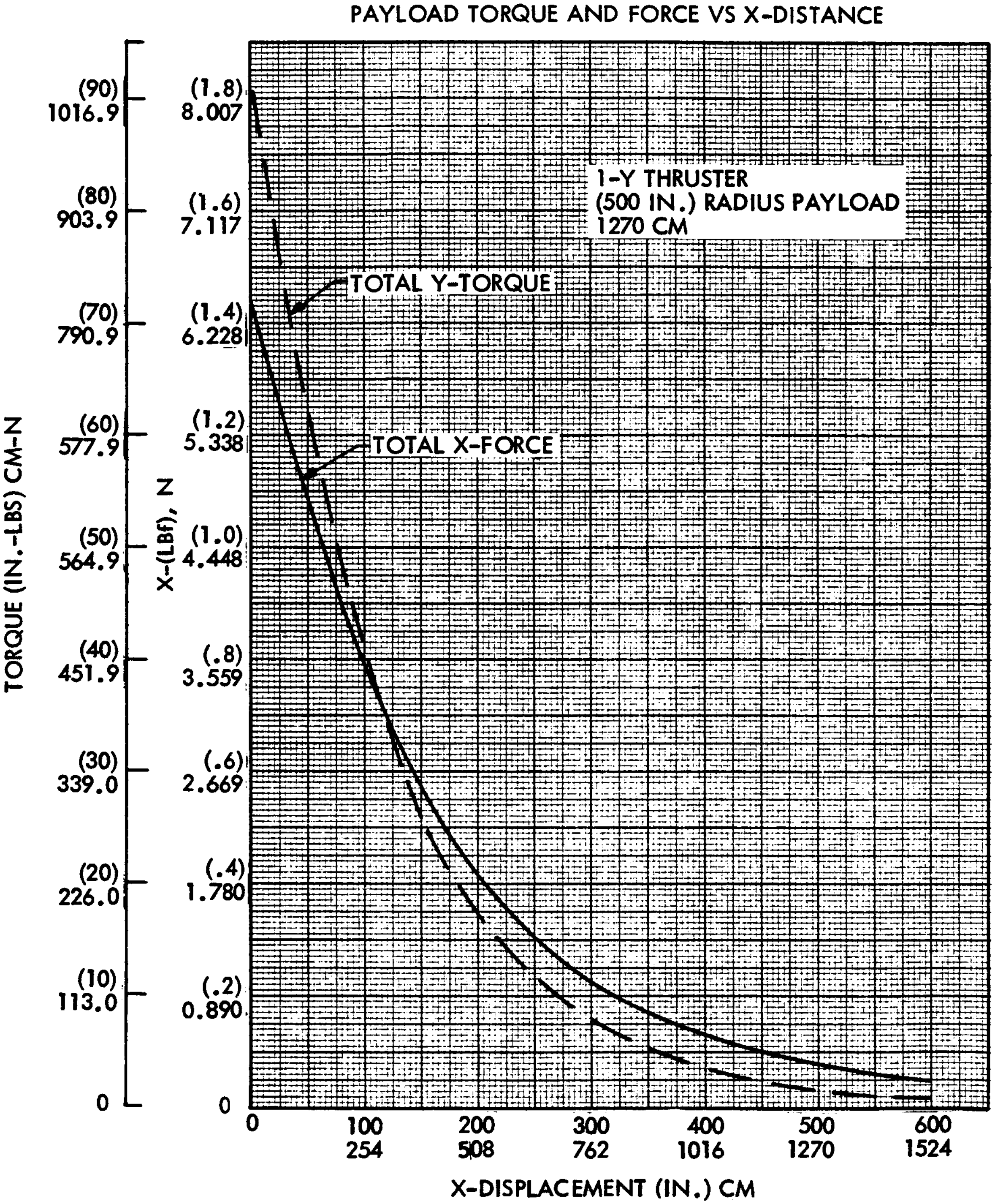

FIG. 7-18 PAYLOAD TORQUE AND FORCE VS X-DISTANCE NORMAL THRUSTER

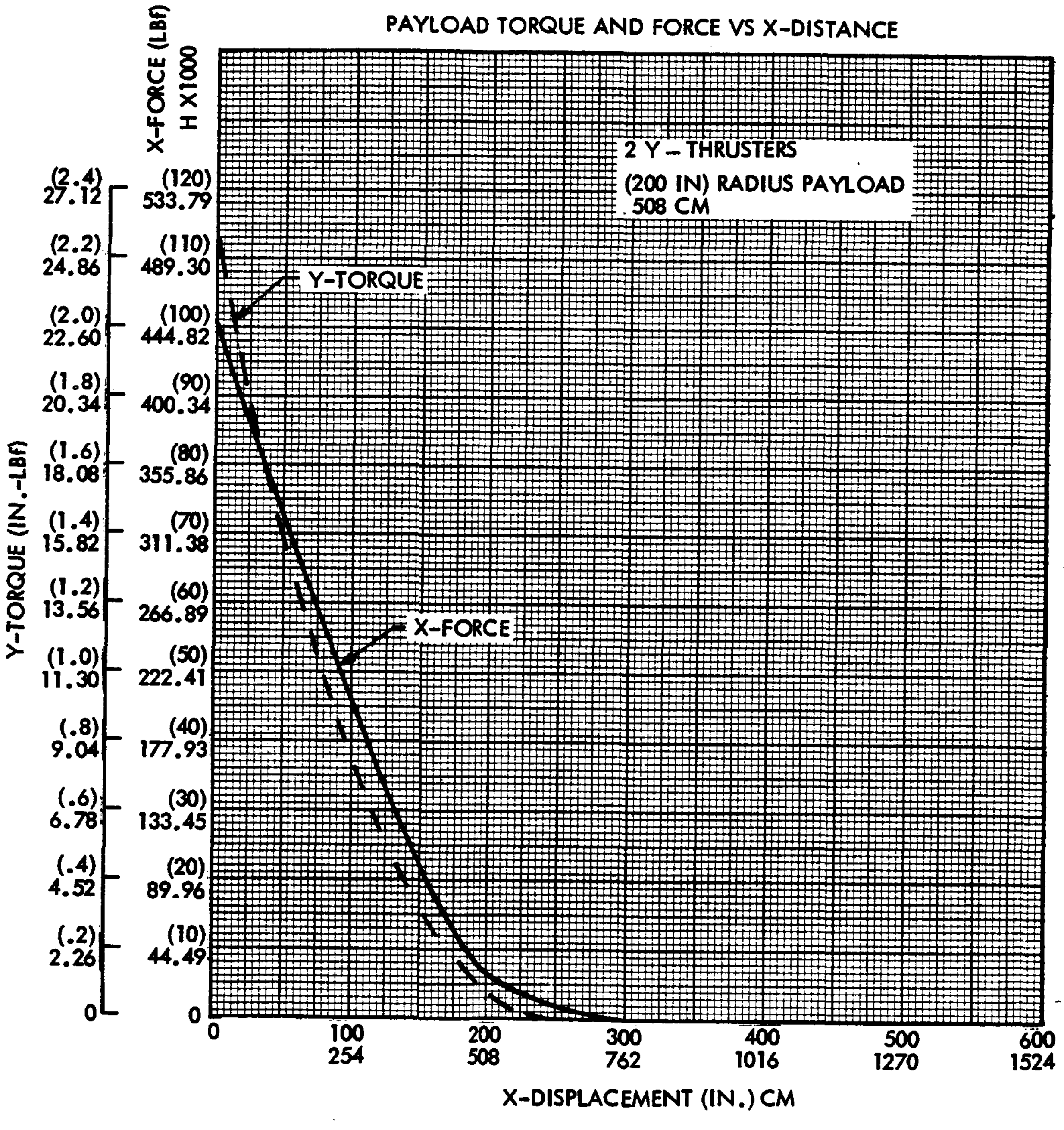

FIG. 7-19 PAYLOAD TORQUE AND FORCE VS X-DISTANCE NORMAL THRUSTERS

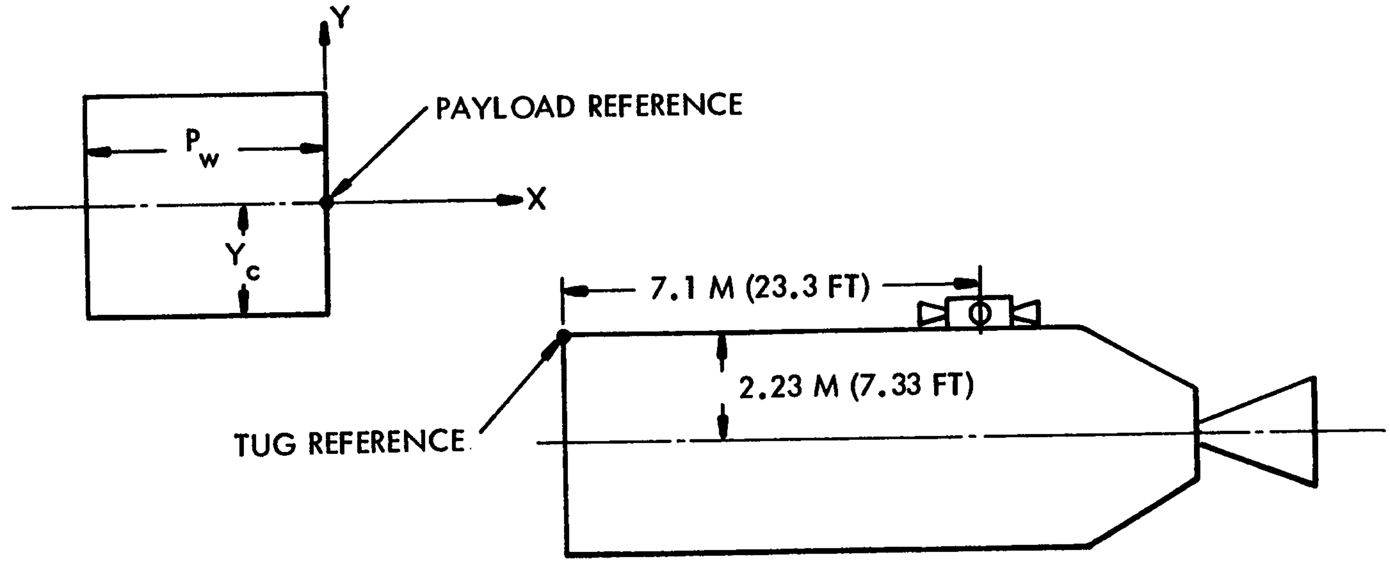

Fig. 7-20 Abort Calculation Coordinates

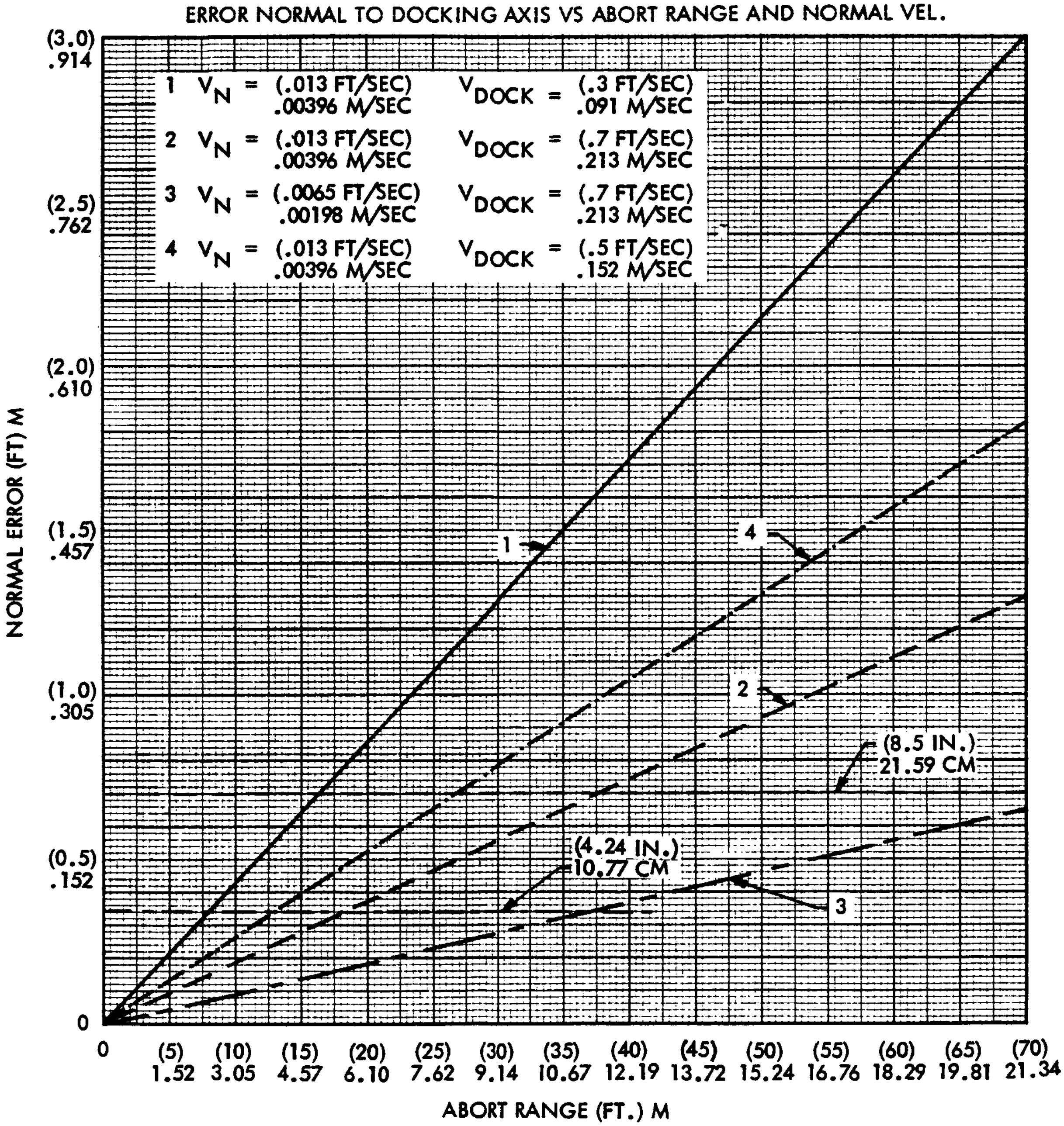

FIG. 7-21 ERROR NORMAL TO DOCKING AXIS VS ABORT RANGE AND NORMAL VELOCITY

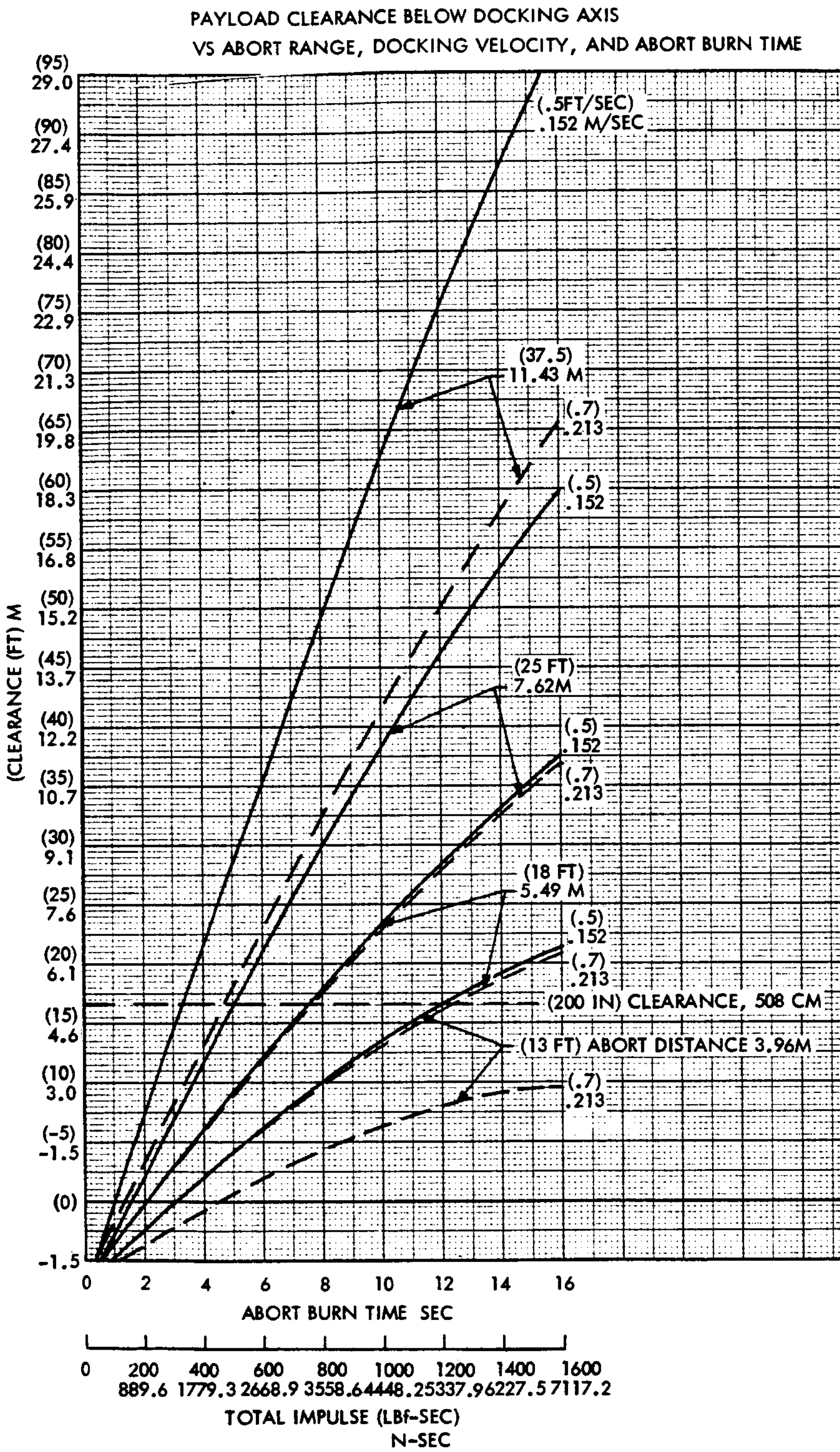

FIG. 7-22 PAYLOAD CLEARANCE BEFORE DOCKING AXIS VS ABORT RANGE, DOCKING VELOCITY AND ABORT BURN TIME

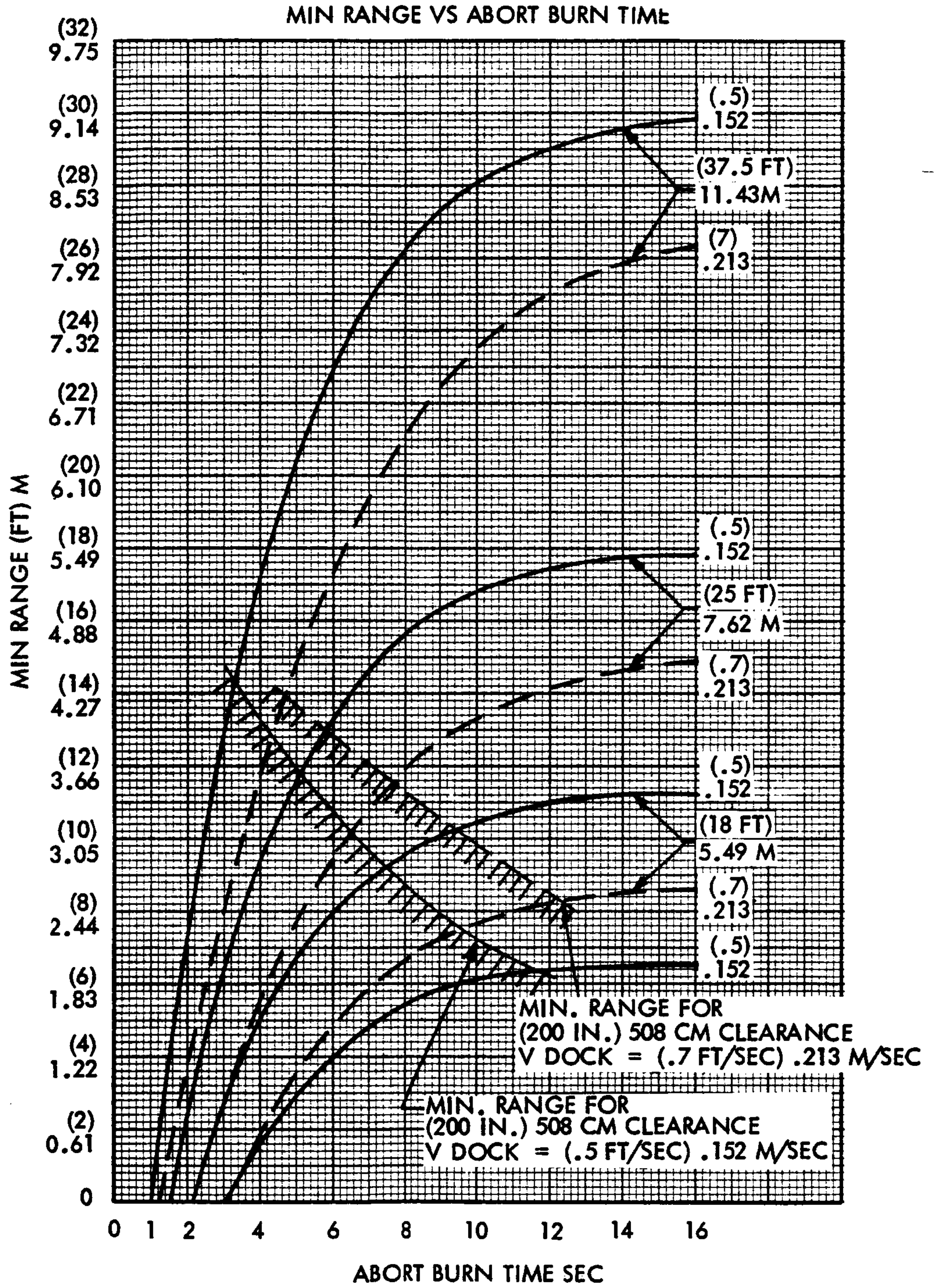

FIG. 7-23 MINIMUM BURN TIME VS ABORT BURN TIME

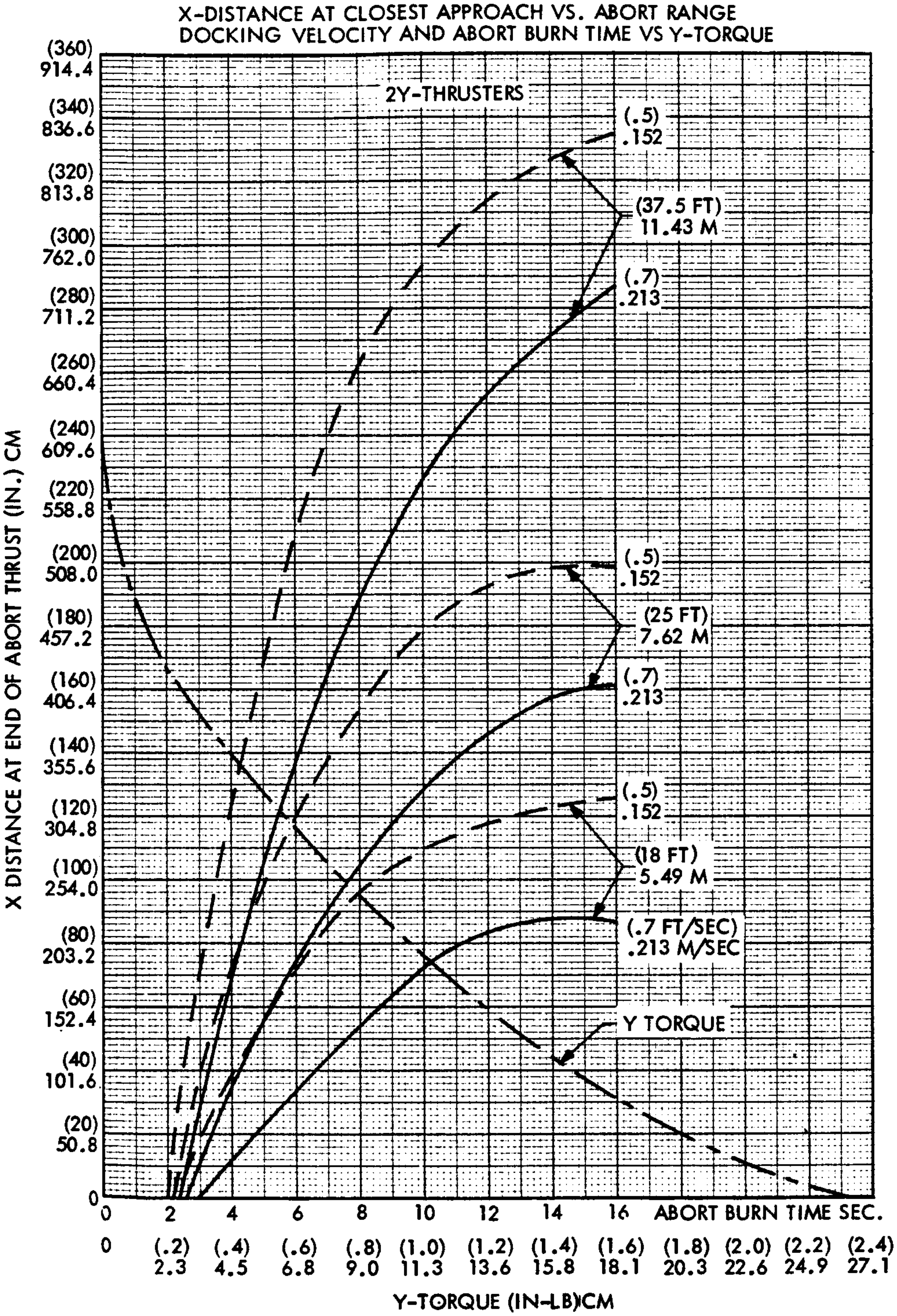

FIG. 7-24 V-DISTANCES AT CLOSEST APPROACH VS ABORT RANGE DOCKING VELOCITY AND ABORT BURN TIME VS Y-TORQUE

Section 8
LOCDOK SIMULATION AND USER'S MANUAL

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.

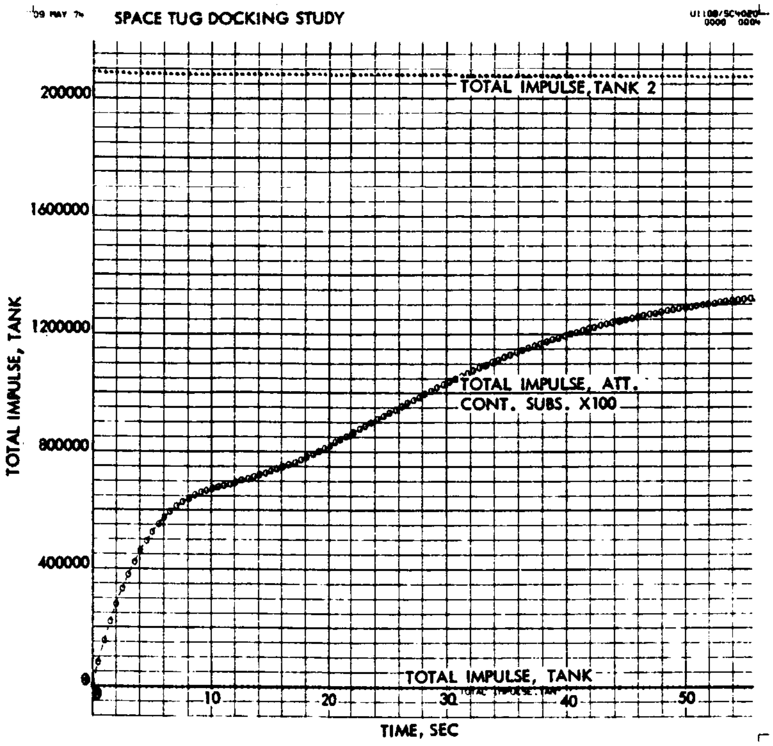

FIG. 8-1 COMPUTER PLOT - ATTITUDE CONTROL TOTAL IMPULSE

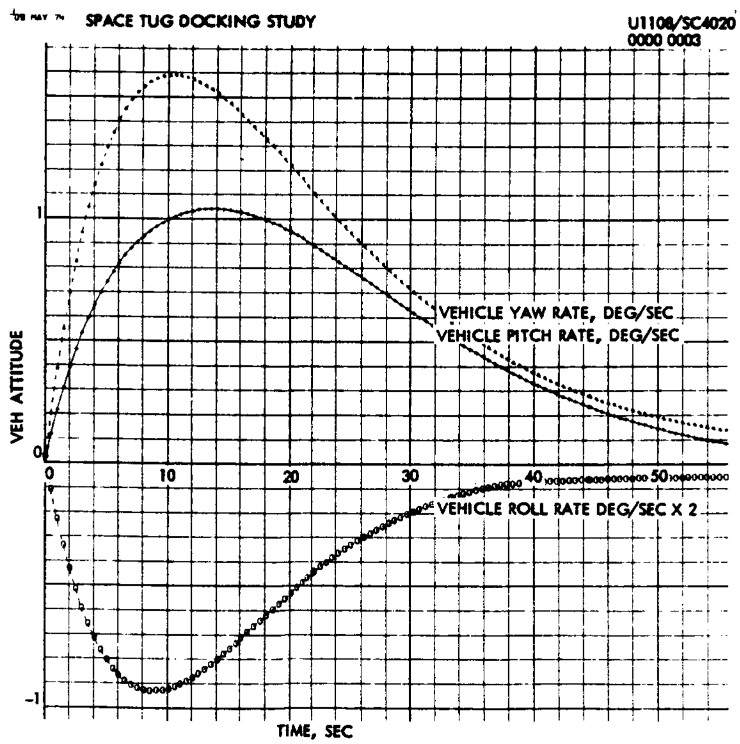

FIG. 8-2 COMPUTER PLOT - REORIENTATION OF TUG TO ACQUIRE PAYLOAD

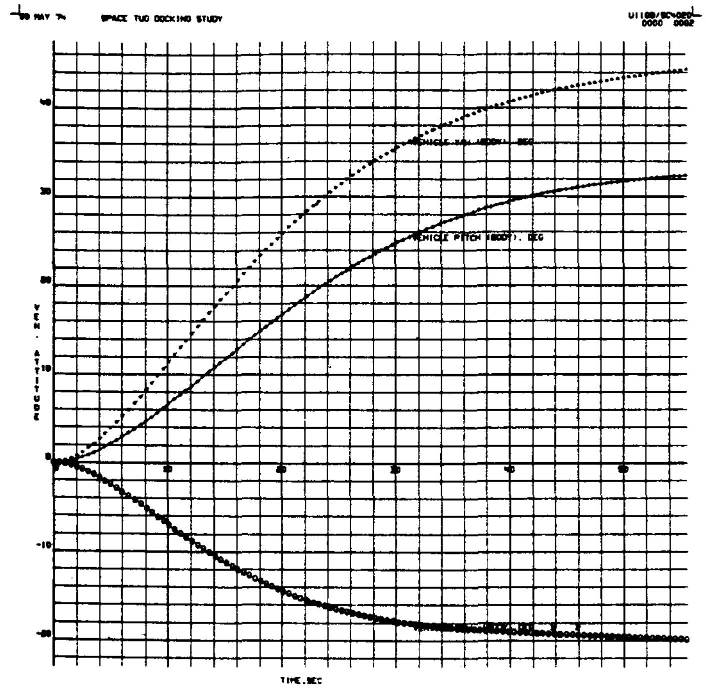

FIG. 8-3 COMPUTER PLOT - TUG ATTITUDE

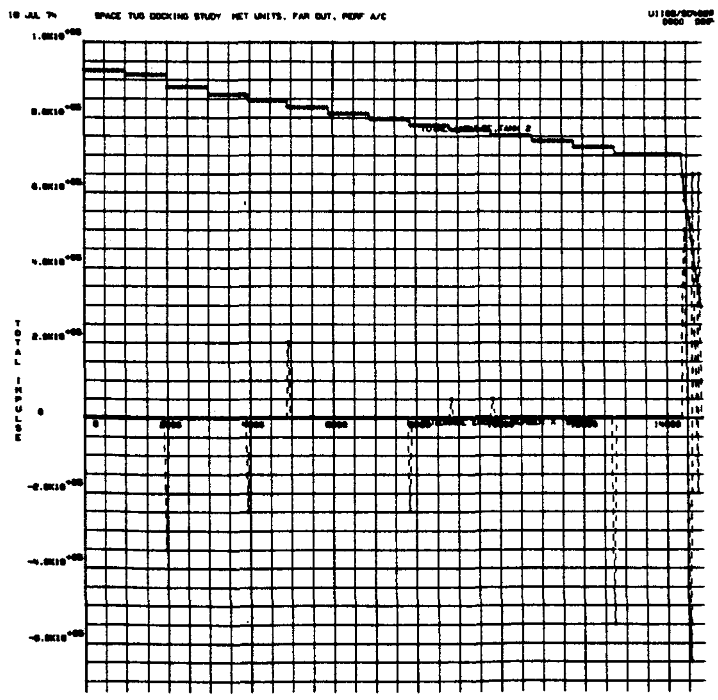

FIG. 8-4 COMPUTER PLOT - APS TOTAL IMPULSE AND ENGINE NO.

C-2

```
                         *** DOCKING MANEUVER DATA ***

              SPACE TUG DOCKING STUDY

                              PROGRAM CONTROLS
INTEGRATION STEP SIZE = .15000000+00      PRINT CYCLE =400STEPS        MAX. TIME =   .17000000+05

                         METRIC UNITS WILL BE USED IN THIS RUN

                              GUIDANCE PARAMETERS
          LCS ENGINE CONTROL (FK)              STANDOFF RANGE
           FK                                  RB
          .10000000+11      .00000000         .12192000+06      .41757600+01

                              PROPULSION PARAMETERS

 MAIN ENG. ISP    AXIAL ENG. ISP   LATERAL ENG ISP  MAIN ENG THRUST  AXIAL ENG THRUST  LATERAL ENG THRUST
 .44400000+03     .23000000+03     .23000000+03     .66723300+05     .44482200+03      .44482200+03
SPS MINIMUM IMPULSE BIT =   .11120550+02   PERCENT ERROR IN DELTA V=   .00000000

              PERFECT ATTITUDE CONTROL IS ASSUMED (INSTANTANEOUS RESPONSE)
```

FIG. 8-5 COMPUTER OUTPUT - SI UNITS, PERFECT ATTITUDE CONTROL - INPUT VARIABLES

SENSOR NOISE CONSTANTS

	RANGE		RANGE RATE		AZ LOS RATE		EL LOS RATE	
BANDWIDTH	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03
MULTIPLIER	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01
EXPONENT	.10000000+01	.00000000	.10000000+01	.00000000	.10000000+01	-.10000000+01	.10000000+01	-.10000000+01
LOWER RANGE LIMIT	.30480000+00	.30480000+00	.30480000+00	.30480000+00	.30480000+00	.30480000+00	.30480000+00	.30480000+00
UPPER RANGE LIMIT	.14371520+06	.14371520+06	.14371520+06	.14371520+06	.14371520+06	.14371520+06	.14371520+06	.14371520+06
STANDARD DEVIATION	.72650604+01	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000

NOISE CONSTANTS CONTINUED

	AZIMUTH (LOS)		ELEVATION (LOS)	
BANDWIDTH (OMEGSR)	.31415940+03	.31415940+03	.31415940+03	.31415940+03
MULTIPLIER (RSTAR)	.10000000+01	.10000000+01	.10000000+01	.10000000+01
EXPONENT (P)	.10000000+01	-.10000000+01	.10000000+01	-.10000000+01
LOWER RANGE (RL)	.30480000+00	.30480000+00	.30480000+00	.30480000+00
UPPER RANGE (RU)	.14371520+06	.14371520+06	.14371520+06	.14371520+06
STANDARD DEVIATIONS (SIGSR)	.29085500-03	.13087800-06	.29085500-03	.13087800-06

SENSOR RESOLUTION AND BIAS INPUTS

RANGE	RANGE RATE	AZ RATE RAD/SEC	EL RATE RAD/SEC	AZ RAD	EL RAD
.91440000-01	.00000000	.00000000	.00000000	.43633231-04	.43633231-04
RANGE BIAS	RANGE RATE BIAS	AZ RATE BIAS	EL RATE BIAS	AZ BIAS	EL BIAS
.00000000	.00000000	.00000000	.00000000	.00000000	.00000000

OTHER INPUT VALUES

TUG DRY MASS =	.23413694+04	TUG MAIN ENG FUEL MASS =	.12057626+05
TUG AUX. ENG FUEL MASS =	.41189824+03	TUG TOTAL MASS =	.14810894+05
TIME BETWEEN DATA POINTS, FAST DATA TAKE=	.30000000+00	TIME ALLOWED FOR BURN COMPUTATIONS=	.10000000+01
NO. OF DATA POINTS FAST DATA TAKE=	100		
MAXIMUM TIME FOR TRANSFER TO DOCK AXIS=	.13500000+05	SENSOR F.O.V. HALF-ANGLE=	.30000000+02
MINIMUM TIME FOR TRANSFER TO DOCK AXIS=	.10000000+02	PERCENT ERROR IN DELTA V=	.00000000
MISS DISTANCE THRESHOLD =	.60960000+01	MIN DIST FOR TRANSFER CALC. (DMIN)=	.60960000-01
SENSOR ACQUISITION RANGE (KM) =	.14371520+03		

DOCKING PARAMETERS

ORIENTATION OF PAYLOAD DOCKING AXIS (DIRECTION COSINES)

UNR2 1 = -.10000000+01 UNR2 2 = .00000000 UNR2 3 = .00000000

MINIMUM RANGE ALLOWED ON DOCKING AXIS IN PLANNING GROSS TRANSFER TO DOCKING AXIS = .30480000+03

ABSOLUTE VALUE OF RANGE RATE DESIRED AT START OF DOCKING MANEUVER (VOD) FT/SEC = .15240000+01

RANGE AT WHICH RANGE RATE IS REDUCED TO FINAL DOCKING VELOCITY (RSUBD) = .41757600+01 (ALSO ABORT RANGE)

DESIRED FINAL IMPACT SPEED (VDOCK) = .15240000+00 VELOCITY PERMITTED AT RSUBD (TOLVEL(1)) = .15240000+00

FIG. 8-5 (CON'T)

```
                              D O C K I N G   M A N E U V E R   B E G I N S
     TIME    =    .00000000            TIMAX =  .20000000+003

                          RELATIVE COORDINATES OF TUG W.R.T. PAYLOAD
         CT =     -.59264000+05        R =    -.59264000+05         IT =    -.55560000+05
      CTCOT =      .42669999+01     RDOT =     .42669999+01      ITDOT =     .36580000+01

ORBIT ELEMENTS OF PAYLOAD SATELLITE,
          ECCENTRICITY  SEM-MAJ-AXIS      INCLIN       CENT ANGLE     ARG OF PERI     RIGHT ASC       TIME
          .26786327-03  .42145788+08    .82850876-04  .90000000+02  -.90000000+02  -.90000000+02  .00000000

ORBIT ELEMENTS OF TUG,
          ECCENTRICITY  SEM-MAJ-AXIS      INCLIN       CENT ANGLE     ARG OF PERI     RIGHT ASC       TIME
          .25099051-02  .42009944+08    .11341480+00  .13460886+03  -.11989184+02  -.13468453+03  .00000000

                                            INERTIAL PARAMETERS
                     TUG POSITION                                               PAYLOAD POSITION

               XI    =   .42097812+008                                  XT    =   .42157074+008
               YI    =  -.55560000+005                                  YT    =   .00000000
               ZI    =   .59324874+005                                  ZT    =   .60960000+002

                     TUG VELOCITY                                               PAYLOAD VELOCITY

               XID   =   .83189993+001                                  XTD   =   .00000000
               YID   =   .30738535+004                                  YTD   =   .30745176+004
               ZID   =  -.42669879+001                                  ZTD   =   .00000000

ACQUISITION RANGE (KM) = .14371520+03   (METERS) = .14371520+06     INITIAL RANGE (KM) = .10055519+03   (METERS) = .10055519+06
ACQUISITION RANGE EXCEEDS INITIAL RANGE

        NOMINAL LOOK ANGLES (RADIANS), RANGE (KM), AND SYSTEM TIME (SEC)      ( RELATIVE TO ORBITAL FRAME )

          AZIM. =  -8.1764288-01      ELEV. =   6.3027615-01      RANGE =   1.0055519+02      TIME =    0.0000000

          AZIM. =  -1.0580021+00      ELEV. =   1.3274222+00      RANGE =   1.2121689+02      TIME =    2.0209961+03

          AZIM. =  -1.3184914+00      ELEV. =  -4.8900824-01      RANGE =   6.5366603+01      TIME =    4.0419921+03

          AZIM. =  -1.3464443+00      ELEV. =   1.2056925+00      RANGE =   1.4867100+02      TIME =    6.0629882+03

          AZIM. =  -2.9772512+00      ELEV. =  -1.3182530+00      RANGE =   6.1046863+02      TIME =    8.0839842+03

          AZIM. =  -1.7921510+00      ELEV. =   3.0347922-03      RANGE =   6.1564756+01      TIME =    1.0104980+04

NEAREST APPROACH WILL OCCUR IN =   .10104980+05 SEC AND THE RANGE WILL BE    .62461063+05 METERS

DATA TAKING RATE ALTERED TO  .45000000+00 TO MATCH INTEGRATION STEP SIZE
TOTAL TRACKING INTERVAL RESET TO  .44549999+02 SEC     TRACKING INTERVAL WILL END WHEN TIME = .44549999+02 SEC

HPG = .15000000+00   HPGI = .45000000+00   HPB = .45000000+00

     TIME =   .00000000
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD,
    IN-TRACK POSITION (XS) =-.55560000+05     IN-TRACK VELOCITY (XSD) = .36579965+01
      RADIAL POSITION (YS) =-.59263914+05       RADIAL VELOCITY (YSD) = .42669998+01
 CROSS-TRACK POSITION (ZS) =-.59264000+05  CROSS-TRACK VELOCITY (ZSD) = .42669999+01
```

FIG. 8-6 COMPUTER OUTPUT - SI UNITS, PERFECT ATTITUDE CONTROL - DATA

```
                                    FINAL VALUES FOLLOW

     TIME =  .44100000+002
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
   IN-TRACK POSITION (XS) =-.55400895+05     IN-TRACK VELOCITY (XSD) = .36309462+01
     RADIAL POSITION (YS) =-.59078076+05       RADIAL VELOCITY (YSD) = .42489882+01
CROSS-TRACK POSITION (ZS) =-.59077467+05  CROSS-TRACK VELOCITY (ZSD) = .42807961+01

                     RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL TIME= .00000000
                    EXTRACTED RANGE VECTOR                              EXTRACTED REL VEL VECTOR
                           RSHATV                                              VSHATV
                IN-TRACK=  -.55560000+05                            IN-TRACK=   .36579660+01
                  RADIAL=  -.59263915+05                              RADIAL=   .42669989+01
             CROSS-TRACK=  -.59264001+05                         CROSS-TRACK=   .42670290+01

STANDARD DEVIATIONS ASSOCIATED WITH EXTRACTED DATA
                       POSITION
      IT                 RAD              CT
 .27745744+02       .27069075+02     .28748556+02

                    POSITION REL TO PAYLCAD                          VELOCITY REL TO PAYLOAD
                           PSONEV                                              VSONEV
                     IT =  -.55398988+05                                VIT =   .36441685+01
                    RAD =  -.59075479+05                               VRAD =   .42788271+01
                     CT =  -.59075826+05                                VCT =   .42670290+01

                  DESIRED FINAL RANGE VECTOR                       DESIRED FINAL VELOCITY VECTOR
                           PSTHOV                                               VFV
                IN TRACK=  -.30480000+03                            IN TRACK=   .15240000+01
                  RADIAL=   .00000000                                 RADIAL=   .00000000
             CROSS TRACK=   .00000000                            CROSS TRACK=   .00000000

DISTANCE NORMAL TO DOCKING AXIS = .83545589+05
MAXIMUM TOLERABLE DISTANCE FROM DOCKING AXIS FOR RETRO-REFLECTOR VIEWING = .31984620+05
TUG IS NOT WITHIN VIEWING LIMITS OF RETRO-REFLECTORS ON PAYLOAD DOCKING AXIS

                          PRELIMINARY APPRAISAL OF GROSS TRANSFER TO DOCKING AXIS
TIME TO BE SPENT IN EACH TRACKING SESSION. SEC = .29700000+02

POSITION-RELATIVE-TO-PAYLOAD TO BE REACHED IN THIS MANEUVER
RSTHOV(1) =-.30480000+03     RSTHOV(2) = .00000000         RSTHOV(3) = .00000000

CURRENT KNOWLEDGE OF TUG'S POSITION RELATIVE TO THE PAYLOAD
RTOCIV(1) =-.55399261+05     RTOCIV(2) =-.59076165+05      RTOCIV(3) =-.59075541+05
RANGE TO PAYLOAD = .10024466+06      DISTANCE TO BE TRAVERSED = .10007653+06
RANGE RATE =-.70221335+01   MAXIMUM POSSIBLE TIME AT PRESENT RATE = .14275527+05

FOR A STANDARD DEVIATION IN MEASURED POSITION = .29204514+02
AND AN ACCEPTABLE STANDARD DEVIATION IN COMPUTED VELOCITY = .30480000-01
THE SHORTEST TRACKING INTERVAL NEEDED = .95815334+03 SECONDS.

BASED ON    100 DATA POINTS. THE CORRESPONDING CLOSEST SPACING OF MEASUREMENTS = .96783165+01 SECONDS

TO MEET VELOCITY ACCURACY REQUIREMENTS, I HAVE RAISED DATA TAKING RATE TO  .96783165+01 SECONDS BETWEEN MEASUREMENTS
TIME TO BE SPENT IN EACH TRACKING SESSION. SEC = .95815333+03
```

FIG. 8-6 (CON'T)

```
DATA TAKING RATE ALTERED TO  .97499999+01 TO MATCH INTEGRATION STEP SIZE
TOTAL TRACKING INTERVAL RESET TO  .96524998+03 SEC     TRACKING INTERVAL WILL END WHEN TIME = .10093500+04 SEC

HPG = .15000000+00   HPGI = .97499999+01   HFD = .97499999+01


      TIME =  .44100000+002
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
     IN-TRACK POSITION (XS) =-.55399261+05     IN-TRACK VELOCITY (XSD) = .36306679+01
       RADIAL POSITION (YS) =-.59076165+05       RADIAL VELOCITY (YSD) = .42488022+01
  CROSS-TRACK POSITION (ZS) =-.59075541+05  CROSS-TRACK VELOCITY (ZSD) = .42809381+01


                              FINAL VALUES FOLLOW

      TIME =  .99959999+003
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
     IN-TRACK POSITION (XS) =-.52233443+05     IN-TRACK VELOCITY (XSD) = .30732921+01
       RADIAL POSITION (YS) =-.55245736+05       RADIAL VELOCITY (YSD) = .38483661+01
  CROSS-TRACK POSITION (ZS) =-.54889009+05  CROSS-TRACK VELOCITY (ZSD) = .45689294+01

                     RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL TIME= .44099999+02
                    EXTRACTED RANGE VECTOR                                EXTRACTED REL VEL VECTOR
                           RSHATV                                              VSHATV
                IN-TRACK=  -.55399261+05                         IN-TRACK=   .36306524+01
                  RADIAL=  -.59075896+05                           RADIAL=   .42488022+01
             CROSS-TRACK=  -.59075542+05                      CROSS-TRACK=   .42809383+01

STANDARD DEVIATIONS ASSOCIATED WITH EXTRACTED DATA
                  POSITION
      IT            RAD            CT
  .11260177+02  .10846908+02  .11235901+02
                          END OF PRELIMINARY APPRAISAL
```

FIG. 8-6 (CON'T)

```
                                        START OF GROSS TRANSFER
ACTUAL DURATION OF BURN OR TRACKING INTERVAL (SEC) = .95549998+03

                POSITION REL TO PAYLOAD                          VELOCITY REL TO PAYLOAD
                        RSONEV                                           VSONEV
               IT =  -.52072386+05                            VIT =  .33329795+01
              RAD =  -.54894643+05                           VRAD =  .45031672+01
               CT =  -.54985105+05                            VCT =  .42809383+01

                                        GROSS CORRECTION COMPUTATIONS

                 RANGE VEC AT BURN                                REL VEL AT BURN
                       ESONEV                                          VSONEV

          IN TRACK=  -.52072386+05                        IN TRACK=  .33329795+01
            RADIAL=  -.54894643+05                          RADIAL=  .45031672+01
       CROSS TRACK=  -.54985105+05                     CROSS TRACK=  .42809383+01

                          INITIAL GUIDANCE COMPUTATIONS TO START TRANSFER

DISTANCE TO BE TRAVERSED, METERS = .93363090+05

PRESENT SPEED TOWARD FINAL OBJECTIVE   .70169902+01  (PARALLEL TO RANGE VECTOR)

MISS DISTANCE ACCEPTABLE

PRESENT SPEED TOWARD FINAL OBJECTIVE   .70175709+01  (PARALLEL TO RANGE VECTOR)
CURRENT VELOCITY COMPONENT IN THE ETA DIRECTION-.66410434+00      COMPONENT NORMAL TO ETA DIRECTION .16225311+00
TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION .68363781+00
JUST TO CANCEL CURRENT NORMAL VELOCITIES WILL REQUIRE  .22762558+02 SECONDS
DESIRED VELOCITY COMPONENT IN THE ETA DIRECTION .12690106+01      COMPONENT IN THE ZETA DIRECTION .00000000
TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION .12690106+01
JUST TO DEVELOP DESIRED NORMAL VELOCITIES WILL REQUIRE  .42253265+02 SECONDS
EXPECTED DURATION OF TRANSFER USING EXISTING RANGE RATE IS LESS THAN MAXIMUM ALLOWED

                                        FINAL CALCULATIONS

PRESENT SPEED TOWARD FINAL OBJECTIVE   .70169902+01  (PARALLEL TO RANGE VECTOR)
CURRENT VELOCITY COMPONENT IN THE ETA DIRECTION-.66410434+00      COMPONENT NORMAL TO ETA DIRECTION .16225311+00
TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION .68363781+00
JUST TO CANCEL CURRENT NORMAL VELOCITIES WILL REQUIRE  .22762558+02 SECONDS
DESIRED VELOCITY COMPONENT IN THE ETA DIRECTION .12690106+01      COMPONENT IN THE ZETA DIRECTION .00000000
TOTAL VELOCITY VECTOR NORMAL TO TRANSFER DIRECTION .12690106+01
JUST TO DEVELOP DESIRED NORMAL VELOCITIES WILL REQUIRE  .42253265+02 SECONDS

DURATION OF NOMINAL FINAL BURN, SEC = .13769331+03   DURATION OF TRACKING BEFORE FINAL BURN, SEC = .95815333+03
```

FIG. 8-6 (CON'T)

```
              EXPECTED MISS DIST                  TRANSFER SPEED              DISTANCE/SPEED
              RSURM  =     .33542163+03      VSO    =    .70175709+01      TSURT  =    .13208546+05

                                              BURN VECTOR
                  DELTA VIT =   .55301076+00   DELTA VRAD =  -.37473863+00    DELTA VCT =  -.14554739+00
                    DESIRED BURN MAG            ACTUAL BURN MAG
                    DELVB  =    .68369144+00    DELVBA  =     .68369144+00   TIME OF BURN =  .99959999+003
   COMPONENTS OF BURN RELATIVE TO BODY AXES
         X =-.35093436-02   Y = .15226556+00   Z = .68078575+00

   DATA TAKING RATE ALTERED TO  .97499999+01 TO MATCH INTEGRATION STEP SIZE
   DURATION OF VELOCITY COMPONENT BURNS (SEC)  X = .11718792+00   Y = .50703305+01   Z = .22664143+02

   LONGEST BURN TIME ON ONE ENGINE IN THIS BURN-SET = .22664143+02 SEC
   SHORTEST BURN TIME ON ONE ENGINE IN THIS BURN-SET = .11718792+00 SEC
   THIS BURN WILL END WHEN TIME IS APPROXIMATELY =   .10222641+04

   DATA TAKING RATE ALTERED TO  .97495999+01 TO MATCH INTEGRATION STEP SIZE
   DURATION OF X-AXIS BURN IS LESS THAN INTEGRATION STEP SIZE AND WILL BE NEGLECTED


                    SIMULATION OF INTERCEPTOR BURN BY NUMERICAL INTEGRATION OF THRUST

   HPG = .15000000+00   HPGI = .15000000+00   HFD = .97499999+01

         TIME =  .99959999+003
   CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
        IN-TRACK POSITION (XS) =-.52203505+05     IN-TRACK VELOCITY (XSD) = .30678353+01
          RADIAL POSITION (YS) =-.55208235+05       RADIAL VELOCITY (YSD) = .38441401+01
     CROSS-TRACK POSITION (ZS) =-.54844448+05  CROSS-TRACK VELOCITY (ZSD) = .45717866+01
```


FIG. 8-6 (CON'T)

```
                         *** DOCKING MANEUVER DATA ***

              SPACE TUG DOCKING STUDY

                              PROGRAM CONTROLS
  INTEGRATION STEP SIZE = .15000000+00    PRINT CYCLE =400STEPS        MAX. TIME =   .17000000+09

                       ENGLISH UNITS WILL BE USED IN THIS RUN

                              GUIDANCE PARAMETERS
           LOS ENGINE CONTROL (FK)          STANDOFF RANGE
             FK                                RR
           .10000000+11     .00000000      .40000000+06      .13700000+02

                              PROPULSION PARAMETERS

  MAIN ENG. ISP   AXIAL ENG. ISP   LATERAL ENG ISP  MAIN ENG THRUST  AXIAL ENG THRUST  LATERAL ENG THRUST
  .44400000+03    .23000000+03     .23000000+03     .15000000+05     .10000000+03      .10000000+03
  SPS MINIMUM IMPULSE BIT =   .25000000+01   PERCENT ERROR IN DELTA V=   .00000000

              PERFECT ATTITUDE CONTROL IS ASSUMED (INSTANTANEOUS RESPONSE)
```

FIG. 8-7 COMPUTER OUTPUT - ENGLISH UNITS PERFECT ATTITUDE CONTROL INPUT VARIABLES

SENSOR NOISE CONSTANTS

	RANGE		RANGE RATE		AZ LOS RATE		EL LOS RATE	
BANDWIDTH	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03	.31415900+03
MULTIPLIER	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01
EXPONENT	.10000000+01	.00000000	.10000000+01	.00000000	.10000000+01	-.10000000+01	.10000000+01	-.10000000+01
LOWER RANGE LIMIT	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01	.10000000+01
UPPER RANGE LIMIT	.47150656+06	.47150656+06	.47150656+06	.47150656+06	.47150656+06	.47150656+06	.47150656+06	.47150656+06
STANDARD DEVIATION	.23835500+02	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000	.00000000

NOISE CONSTANTS CONTINUED

	AZIMUTH (LOS)		ELEVATION (LOS)	
BANDWIDTH (OMEGSR)	.31415940+03	.31415940+03	.31415940+03	.31415940+03
MULTIPLIER (RSTAR)	.10000000+01	.10000000+01	.10000000+01	.10000000+01
EXPONENT (P)	.10000000+01	-.10000000+01	.10000000+01	-.10000000+01
LOWER RANGE (RL)	.10000000+01	.10000000+01	.10000000+01	.10000000+01
UPPER RANGE (RU)	.47150657+06	.47150657+06	.47150657+06	.47150657+06
STANDARD DEVIATIONS (SIGSR)	.29085500-03	.13087800-06	.29085500-03	.13087800-06

SENSOR RESOLUTION AND BIAS INPUTS

RANGE	RANGE RATE	AZ RATE RAD/SEC	EL RATE RAD/SEC	AZ RAD	EL RAD
.10000000+00	.00000000	.00000000	.00000000	.25000000-02	.25000000-02
RANGE BIAS	RANGE RATE BIAS	AZ RATE BIAS	EL RATE BIAS	AZ BIAS	EL BIAS
.00000000	.00000000	.00000000	.00000000	.00000000	.00000000

OTHER INPUT VALUES

TUG DRY MASS =	.16043480+03	TUG MAIN ENG FUEL MASS =	.87621000+03
TUG AUX. ENG FUEL MASS =	.28200000+02	TUG TOTAL MASS =	.10148448+04
TIME BETWEEN DATA POINTS, FAST DATA TAKE=	.15000000+00	TIME ALLOWED FOR BURN COMPUTATIONS=	.10000000+01
NO. OF DATA POINTS FAST DATA TAKE=	100		
MAXIMUM TIME FOR TRANSFER TO DOCK AXIS=	.13500000+05	SENSOR F.O.V. HALF-ANGLE=	.30000000+02
MINIMUM TIME FOR TRANSFER TO DOCK AXIS=	.10000000+02	PERCENT ERROR IN DELTA V=	.00000000
MISS DISTANCE THRESHOLD =	.20000000+02	MIN DIST FOR TRANSFER CALC. (DMIN)=	.20000000+00
SENSOR ACQUISITION RANGE (NM) =	.77600000+02		

DOCKING PARAMETERS

ORIENTATION OF PAYLOAD DOCKING AXIS (DIRECTION COSINES)

UNR2 1 = -.10000000+01 UNR2 2 = .00000000 UNR2 3 = .00000000

MINIMUM RANGE ALLOWED ON DOCKING AXIS IN PLANNING GROSS TRANSFER TO DOCKING AXIS = .10000000+04

ABSOLUTE VALUE OF RANGE RATE DESIRED AT START OF DOCKING MANEUVER (VOD) FT/SEC = .50000000+01

RANGE AT WHICH RANGE RATE IS REDUCED TO FINAL DOCKING VELOCITY (RSUBD) = .13700000+02 (ALSO ABORT RANGE)

DESIRED FINAL IMPACT SPEED (VDOCK) = .50000000+00 VELOCITY PERMITTED AT RSUBD (TOLVEL(1)) = .50000000+00

FIG. 8-7 (CON'T)

```
                              D O C K I N G   M A N E U V E R   B E G I N S

      TIME   =   .00000000              TIMAX =  .17000000+005

                              RELATIVE COORDINATES OF TUG W.R.T. PAYLOAD
            CT =    -.19443600+06        R =    -.19443600+06        IT =    -.18228300+06
         CTDOT =     .14000000+02     RDOT =     .14000000+02     ITDOT =     .12000000+02

   ORBIT ELEMENTS OF PAYLOAD SATELLITE.
            ECCENTRICITY  SEM-MAJ-AXIS       INCLIN        CENT ANGLE     ARG OF PERI      RIGHT ASC       TIME
            .26781857-03  .13827359+09   .82850876-04   .90000000+02  -.90000000+02  -.90000000+02   .00000000

   ORBIT ELEMENTS OF TUG.
            ECCENTRICITY  SEM-MAJ-AXIS       INCLIN        CENT ANGLE     ARG OF PERI      RIGHT ASC       TIME
            .25101399-02  .13782787+09   .11341752+00   .13461016+03  -.11989640+02  -.13468583+03   .00000000

                                                INERTIAL PARAMETERS
      /                 TUG POSITION                                            PAYLOAD POSITION

                  XI      =    .13811618+009                              XT      =    .13831062+009
                  YI      =   -.18228300+006                              YT      =    .00000000
                  ZI      =    .19463572+006                              ZT      =    .20000000+003

                        TUG VELOCITY                                            PAYLOAD VELOCITY

                  XID     =    .27293928+002                              XTD     =    .00000000
                  YID     =    .10084820+005                              YTD     =    .10087000+005
                  ZID     =   -.13999961+002                              ZTD     =    .00000000

   ACQUISITION RANGE (NM) = .77400000+02    (FT) = .47150656+06     INITIAL RANGE (NM) = .54295477+02    (FT) = .32990559+06
   ACQUISITION RANGE EXCEEDS INITIAL RANGE

        NOMINAL LOOK ANGLES (DEGREES), RANGE (NM), AND SYSTEM TIME (SEC)     ( RELATIVE TO ORBITAL FRAME )

          AZIM. =  -4.6847604+01      ELEV. =   3.6112216+01      RANGE =   5.4295476+01      TIME =   0.0000000

          AZIM. =  -4.5212275+01      ELEV. =   3.6275787+01      RANGE =   4.6611631+01      TIME =   2.1510608+03

          AZIM. =  -4.0569729+01      ELEV. =   3.7377949+01      RANGE =   4.0016449+01      TIME =   4.3021215+03

          AZIM. =  -3.2025420+01      ELEV. =   3.9722792+01      RANGE =   3.4773510+01      TIME =   6.4531823+03

          AZIM. =  -1.8720756+01      ELEV. =   4.3142396+01      RANGE =   3.1323972+01      TIME =   8.6042429+03

          AZIM. =  -8.5210711-01      ELEV. =   4.6659308+01      RANGE =   3.0115254+01      TIME =   1.0755304+04

   NEAREST APPROACH WILL OCCUR IN =   .10755304+05 SEC AND THE RANGE WILL BE     .18298312+06 FT
   TOTAL TRACKING INTERVAL RESET TO   .14850000+02 SEC     TRACKING INTERVAL WILL END WHEN TIME = .14850000+02 SEC

   HPG = .15000000+00   HPGI = .15000000+00   HFD = .15000000+00

        TIME =  .00000000
   CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
        IN-TRACK POSITION (XS) =-.18228300+06      IN-TRACK VELOCITY (XSD) = .12000010+02
          RADIAL POSITION (YS) =-.19443572+06        RADIAL VELOCITY (YSD) = .14000000+02
     CROSS-TRACK POSITION (ZS) =-.19443600+06   CROSS-TRACK VELOCITY (ZSD) = .14000000+02
```

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

```
                                   FINAL VALUES FOLLOW

      TIME =  .14780000+03
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
    IN-TRACK POSITION (XS) =-.92357862+03     IN-TRACK VELOCITY (XSD) = .50488813+01
      RADIAL POSITION (YS) = .16532929+02       RADIAL VELOCITY (YSD) = .41946491-01
 CROSS-TRACK POSITION (ZS) =-.19097780+03  CROSS-TRACK VELOCITY (ZSD) =-.37692201-02

                       RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL TIME= .00000000
                       EXTRACTED RANGE VECTOR                              EXTRACTED REL VEL VECTOR
                              RSHATV                                              VSHATV
                   IN-TRACK= -.99703498+01                            IN-TRACK=  .50481499+01
                     RADIAL=  .16000276+02                              RADIAL=  .31236834-01
                CROSS-TRACK= -.19092302+03                         CROSS-TRACK= -.35893134-02

STANDARD DEVIATIONS ASSOCIATED WITH EXTRACTED DATA
                     POSITION
       IT              RAD              CT
  .64062749-02     .35712401+00     .78994879-01


                        POSITION REL TO PAYLOAD                         VELOCITY REL TO PAYLOAD
                               RSONEV                                          VSONEV
                        IT =  -.92202130+03                          VIT =  .50480004+01
                       RAD =   .16539232+02                         VRAD =  .42079193-01
                        CT =  -.19097837+03                          VCT =  -.37650677-02

                      DESIRED FINAL RANGE VECTOR                      DESIRED FINAL VELOCITY VECTOR
                               RSTWOV                                           VFV

                   IN TRACK= -.10000000+04                          IN TRACK=  .50000000+01
                     RADIAL=  .00000000                               RADIAL=  .00000000
                CROSS TRACK=  .00000000                          CROSS TRACK=  .00000000
DISTANCE NORMAL TO DOCKING AXIS = .19169320+03
MAXIMUM TOLERABLE DISTANCE FROM DOCKING AXIS FOR RETRO-REFLECTOR VIEWING = .24726922+03
TUG IS WITHIN RETRO-REFLECTOR VIEWING LIMITS

REMAINING TOTAL MASS = .10078600+04   REMAINING MAIN ENG PROP MASS = .82620999+03   REMAINING APS PROP MASS = .21229000+02



                       **********  TRANSFER TO DOCKING AXIS COMPLETED  **********
```

FIG. 8-8 (CON'T)

```
              DESIRED FINAL RANGE VECTOR                        DESIRED FINAL VELOCITY VECTOR
                        RSTHOV                                              VFV

           IN TRACK=  -.13700000+02                       IN TRACK=   .50000000+00
             RADIAL=   .00000000                            RADIAL=   .00000000
        CROSS TRACK=   .00000000                       CROSS TRACK=   .00000000


                              MIDCOURSE TRACKING COMPUTATIONS

              POSITION REL TO PAYLOAD                      VELOCITY REL TO PAYLOAD
                      RSONEV                                        VSONEV
           IT =  -.92282130+03                          VIT =   .50880004+01
          RAD =   .16539232+02                         VRAC =   .42079193-01
           CT =  -.19097837+03                          VCT =  -.37650677-02


                 STANDARD DEVIATIONS OF NOISE
                     RANGE                    ELEVATION              AZIMUTH
FIRST COMPONENT      .67585927-01             .83550296-06           .83550296-06
SECOND COMPONENT     .00000000                .45561322-05           .45561322-05
ROOT-SUM-SQUARE      .67585927-01             .46321059-05           .46321059-05
TOTAL TRACKING INTERVAL RESET TO  .14850000+02 SEC     TRACKING INTERVAL WILL END WHEN TIME = .29549999+02 SEC

HPG = .15000000+00   HPGI = .15000000+00   HPD = .15000000+00


      TIME =  .14780000+002
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
     IN-TRACK POSITION (XS) =-.92282130+03      IN-TRACK VELOCITY (XSD) = .50880004+01
        RADIAL POSITION (YS) = .16539232+02        RADIAL VELOCITY (YSD) = .42079193-01
  CROSS-TRACK POSITION (ZS) =-.19097837+03  CROSS-TRACK VELOCITY (ZSD) =-.37650677-02
```

FIG. 8-8 (CON'T)

```
                                   FINAL VALUES FOLLOW

      TIME =  .23690000+003
CURRENT POSITION AND VELOCITY RELATIVE TO THE PAYLOAD.
    IN-TRACK POSITION (XS) =-.83485148+01      IN-TRACK VELOCITY (XSD) = .31294901+00
    RADIAL POSITION (YS) = .15679213+00        RADIAL VELOCITY (YSD) = .95871699-02
 CROSS-TRACK POSITION (ZS) = .85075478-01  CROSS-TRACK VELOCITY (ZSD) = .10266415-03

RESULTS CORRESPONDING TO START OF DATA GATHERING INTERVAL TIME= .22200000+03
                      EXTRACTED RANGE VECTOR                           EXTRACTED REL VEL VECTOR
                             RSHATV                                           VSHATV
                  IN-TRACK=  -.16030282+02                        IN-TRACK=   .38376582+00
                    RADIAL=   .17407012+01                          RADIAL=   .10613249-01
               CROSS-TRACK=   .92849407-01                     CROSS-TRACK=  -.27401939-03

STANDARD DEVIATIONS ASSOCIATED WITH EXTRACTED DATA
                      POSITION
      IT                RAD              CT
  .51150797-03      .39519541-01     .47226272-03

ACTUAL DURATION OF BURN OR TRACKING INTERVAL (SEC) = .14700001+02


                      POSITION REL TO PAYLOAD                      VELOCITY REL TO PAYLOAD
                             RSONEV                                       VSONEV
                       IT =  -.83015724+01                      VIT =   .31294880+00
                      RAD =   .15823071+00                     VRAD =   .95940172-02
                       CT =   .85090877-01                      VCT =   .10266408-03

        RESULTS OF TESTS ON ADEQUACY OF SET-UP FOR FINAL APPROACH
ANGLES BETWEEN BODY AXES AND DOCKING AXES
   ROLL = .12241530+01    YAW = .10758840+01    PITCH = .58374964+00

                              IT                 RAD                CT
POSITION TOLERANCE    =   .20000000+01      .50000000+00      .50000000+00
VELOCITY TOLERANCE    =   .20000000+00      .30000000-01      .30000000-01
ANGLE TOLERANCE (DEG) =   .25000000+01      .25000000+01      .25000000+01
CURRENT POSITION =   -.50000001+01      .25944645+00      .86173971-01
CURRENT VELOCITY =    .31294880+00      .95940172-02      .10266408-03

POSITION, VELOCITY, AND BODY-ANGLES ARE ALL ACCEPTABLE.

PROPELLANT REQUIRED IN RETRO MANEUVER = .54598587+01
NEW FINAL PROPELLANT MASS FOR AUXILLIARY SYSTEM = .59692523+02
```

FIG. 8-8 (CON'T)

```
FINAL VALUES AT   .23670000+03 SECONDS.

THE FOLLOWING IS RELATIVE TO THE TARGET.
    IN-TRACK POSITION (XS) =-.50000001+01      IN-TRACK VELOCITY (XSD) = .31294880+00
       RADIAL POSITION (YS) = .25944645+00        RADIAL VELOCITY (YSD) = .99940172-02
 CROSS-TRACK POSITION (ZS) = .86173971-01  CROSS-TRACK VELOCITY (ZSD) = .10266408-03

                DESIRED FINAL RANGE VECTOR                         DESIRED FINAL VELOCITY VECTOR
                          RSTHDV                                                VFV

               IN TRACK=  -.50000000+01                         IN TRACK=   .30000000+00
                 RADIAL=   .00000000                              RADIAL=   .00000000
            CROSS TRACK=   .00000000                         CROSS TRACK=   .00000000

REMAINING TOTAL MASS = .10965025+04   REMAINING MAIN ENG PROP MASS = .82620999+03   REMAINING APS PROP MASS = .59862484+02
                                                          IF RETRO MANEUVER PERFORMED, APS FUEL MASS = .54492523+02

      WEIGHT OF PROPELLANT CONSUMED IN DOCKING, LBS =-.12409848+04      TOTAL DELTA-VEE = .15044726+02

EXTRAPOLATION OF POSITION AND VELOCITY TO FINAL DOCKED POSITION
         TIME OF FINAL DOCK = .26322693+03
    IN-TRACK POSITION (XS) =-.11920929-06      IN-TRACK VELOCITY (XSD) = .31294880+00
       RADIAL POSITION (YS) = .41273057+00        RADIAL VELOCITY (YSD) = .99940172-02
 CROSS-TRACK POSITION (ZS) = .87814241-01  CROSS-TRACK VELOCITY (ZSD) = .10266408-03

         MISS DISTANCES IN INCHES.
    IN-TRACK POSITION MISS = .00000000
       RADIAL POSITION MISS = .49527669+01
          CROSS-TRACK MISS = .10537769+01

                                   *** DOCKING MANEUVER COMPLETED ***
```

FIG. 8-8 (CON'T)

```
                         *** DOCKING MANEUVER DATA ***
                 SPACE TUG DOCKING STUDY

                                PROGRAM CONTROLS
ATTITUDE CONTROL INTEGRATION STEP SIZE =  .10000000-01      PRINT CYCLE =.40081E+03       MAX. TIME =  .20000000+02

                       ENGLISH UNITS WILL BE USED IN THIS RUN

                                GUIDANCE PARAMETERS
          AXIAL ENGINE CONTROL (FK)     STANDOFF RANGE                          LAT. ENG. SWITCH. LINES
          FK                            RB                                      OMHI           OMLO
          .10000000+11   .00000000      .40000000+00      .13700000+02        .30000000-04   .10000000-04
   GUIDANCE FILTER TIME CONSTANT        GUID. DELAY       TIME SWTCH          OMMI           OMLUR
.20000000+02   .30000000+02   .30000000-02  .10000000-02   .00000000          .00000000      .00000000
                                        PROCON            RF                  RFD            RS
                                        .40000000+01      .13700000+02        .13700000+02   .40200447+06

                                PROPULSION PARAMETERS
MAIN ENG. ISP   AXIAL ENG. ISP   LATERAL ENG ISP   MAIN ENG THRUST   AXIAL ENG THRUST   LATERAL ENG THRUST
.44400000+03    .23000000+03     .23000000+03      .15000000+05      .10000000+03       .10000000+03
SPS MINIMUM IMPULSE BIT =   .25000000+01   PERCENT ERROR IN DELTA V=   .00000000

                                ATTITUDE PARAMETERS
            ROLL           YAW            PITCH                ROLL                YAW            PITCH
        MOMENTS OF INERTIA                                     POSITION GAIN
        .52990000+04   .43217000+05   .43440000+05         .78820000+01        .14883700+03   .14782800+03
        RATE GAIN                                              ATTITUDE CONTROL THRUST
        .15724000+03   .29367400+04   .29524800+04         .10000000+03        .10000000+03   .10000000+03
        DEADBANDS                                              MOMENT ARM
        .43630000-02   .43630000-02   .43630000-02         .67500000+01        .29583000+01   .29583000+01
        CONTROL MOMENT TIME CONSTANT                           CHANNEL GAIN
        .00000000      .00000000      .00000000            .14324950+03        .43244991+01   .35374985+01
        MIN IMPULSE BIT
        .16875000+02   .73958000+01   .73958000+01
```

FIG. 8-9 COMPUTER OUTPUT - ENGLISH UNITS, DETAILED ATTITUDE CONTROL INPUT VARIABLES

TIME = .27760000+002   TIMAX = .50000000+003

INERTIAL PARAMETERS

TUG POSITION			PAYLOAD POSITION		
XI	=	.13891035+009	XT	=	.13891034+009
YI	=	.27915695+006	YT	=	.28001493+006
ZI	=	.38958764+003	ZT	=	.19999959+003

TUG VELOCITY			PAYLOAD VELOCITY		
XID	=	-.20537952+002	XTD	=	-.20426756+002
YID	=	.10091590+005	YTD	=	.10086979+005
ZID	=	-.55248104+000	ZTD	=	-.29537509-004

RELATIVE KINEMATICS AND OTHER DATA

RELATIVE TO	IN-TRACK	RADIAL	CROSS-TRACK	V IN-TRACK	V RADIAL	V CROSS-TRACK
PAYLOAD	-.85801251+03	.16399130+02	-.18958802+03	.46097528+01	-.16443723+00	.55245133+00
TUG	.85802279+03	-.16404712+02	.18954103+03	-.46097815+01	.16449593+00	-.55219878+00

DATA RELATIVE TO TUG BODY AXES

	RANGE	RANGE RATE	AZ RATE	EL RATE	ELEVATION	AZIMUTH
TRUE	.87886177+03	-.46226386+01	.51805041-03	.21173675-04	-.25528156+00	-.34278383+00
WITH NOISE	.87870000+03	-.46226386+01	.51805041-03	.21173675-04	-.25500000+00	-.34250000+00
FILTERED NOISE	.87870000+03	-.46226386+01	.51805041-03	.21173675-04	-.25500000+00	-.34250000+00

TUG PARAMETERS

AXIAL THRUST	LATERAL THRUST	TOTAL DELTA VEE	AXIAL NO	LAT NO	PHIA
.10000000+03	.10000000+03	.11331219+01	1	-4	.42692424+00

EULER,	ROLL (RAD)=	.40703415-01	YAW (RAD)=	.10698905+00	PITCH (RAD)=	.25642451+00
BODY ,	ROLL (RAD)=	.30592752-01	YAW (RAD)=	.11255164+00	PITCH (RAD)=	.25127739+00
BODY RATES	ROLL(R/SEC)=	.16518150-02	YAW(R/SEC)=	.10459725-01	PITCH(R/SEC)=	.13693729-01

TOTAL IMPULSE OF ATTITUDE TORQUER JETS (LB-SEC)

ROLL = .28375199+01   YAW = .14712508+03   PITCH = .20003470+03

ATTITUDE CONTROL THRUST

	ROLL	YAW,	PITCH
CMAND	.11603660+00	.86597867+01	.56440086+01
OUT	.78324703+00	.25618247+02	.16696671+02

FIG. 8-10 COMPUTER OUTPUT - ENGLISH UNITS, DETAILED ATTITUDE CONTROL DATA

Section 9

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 affect 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 avery serious problem for the Tug. Potentially it could have an even greater effect on the vehicle then 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 (VDOCK).

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 autonomour 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_m) 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 10-1

NAVIGATION SYSTEM MECHANIZATION SCHEME

NAVIGATION CONCEPT	BASIC NAVIGATION SENSOR (ON SPACECRAFT)	SPECIAL EQUIPMENT ON GROUND OR NAV/DATA RELAY SATELLITE	DATA TRANSMISSION TO GROUND FOR NAVIGATION	SPACECRAFT ATTITUDE DETERMINATION	AUXILIARY SENSING	AUTO-NOMY LEVEL
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	LANDMARK TRACKING TELESCOPE AND STAR TRACKER (MAY BE ONE INTEGRATED SENSOR)	TRANSMITTER OF CODED PULSES GIVING TIME OF TRANSMISSION, TRANSMITTER LOCATION AND CLOCK CALIBRATION DATA	NONE	INERTIAL FRAME DEFINED BY STAR SIGHTINGS. (MAY BE PART OF INTEGRATED SENSOR)	• RECEIVER OF TIMATION CODED PULSES FOR PERIODIC UPDATES AND HORIZON SENSOR FOR INITIALIZATION. (MAY BOTH BE PART OF INTEGRATED SENSOR)	II
NAVIGATION BY GROUND BEACON	TRANSCEIVER (UHF) WITH RANGE DETECTION; MEASURES RANGE TO GROUND TRANSPONDER. (ALSO RANGE RATE; SEE AUXILIARY DEVICE)	TRANSPONDERS PLACE IN NEAR ORBIT PATH	CODED BEACON SIGNAL	NONE REQUIRED FOR NAVIGATION	MEASURE RANGE RATE TO GROUND TRANSPONDER • LOW-G ACCELEROMETER • RADAR ALTIMETER	II
INTERFEROMETER ANGLE MEASUREMENTS FROM EARTH	ANTENNAS/RECEIVERS a. THREE OR 4 ANTENNAS LOCATED ~10 λ APART RECEIVER(S) PHASE DETECTING CIRCUITS FOR DIFFERENTIAL RANGING MEASURES ANGLE FROM GROUND STATION TO SPACECRAFT b. RECEIVER (WITH PHASE DETECTION CIRCUITS FOR DIFFERENTIAL RANGING) MEASURES ANGLE FROM GROUND STATION TO SPACECRAFT	TRANSMITTERS: a. TRANSMITTERS OF KNOWN LOCATIONS AND FREQUENCIES ON EARTH SURFACE b. GROUPS OF 3 SYNCHRONIZED GROUND TRANSMITTERS NEAR THE ORBIT PATH	a. NONE b. NONE	a. NONE REQUIRED FOR NAVIGATION b. NONE REQUIRED FOR NAVIGATION	a. • RADAR ALTIMETER • LOW-G ACCELEROMETER b. • RADAR ALTIMETER • LOW-G ACCELEROMETER	II II
ONE WAY DOPPLER	EXISTING S-BAND RECEIVER	NONE (USE EXISTING S-BAND TRANSMITTER)	NONE	INERTIAL DEFINED BY STAR SIGHTING	• LOW-G ACCELEROMETER	II
GROUND TRACKING	S-BAND OR SGLS TRANSPONDERS WITH RANGING	S-BAND OR SGLS TRANSPONDERS, TRACKING ANTENNAS, GROUND PROCESSOR	CODED RANGING SIGNAL MODULATING DOWN-LINK CARRIER	INERTIAL DEFINED BY STAR SIGHTING	• RADAR ALTIMETER • LOW-G ACCELEROMETER	III
NAVIGATION SATELLITES AND/OR DATA RELAY SATELLITE NAVIGATION BY: A. RANGING	RANGING TRANSCEIVERS EITHER: A_1 UHF/VHF TRANSCEIVER A_2 MICROWAVE TRANSCEIVER A_3 LASER TRANSCEIVER TRANSCEIVERS MEASURE SPACECRAFT TO SPACECRAFT (ALSO RANGE RATE)	TRANSPONDER/ANTENNA: A_1 NONGIMBALLED A_2-A_3 GIMBALLED	ORBIT EPHEMERIS OF NAV/RELAY SATELLITE NEEDED ON SPACECRAFT. ORBIT EPHEMERIS OF SPACECRAFT NEEDED ON NAV/RELAY SATELLITE FOR INITIAL POINTING OF ANTENNA	NONE REQUIRED FOR NAVIGATION. MODERATELY ACCURATE SPACECRAFT ATTITUDE KNOWLEDGE REQUIRED FOR ACQUISITION OF MICROWAVE AND LASER TARGETS	A. MEASURE RANGE RATE BETWEEN SPACECRAFT • LOW-G ACCELEROMETER • RADAR ALTIMETER	III
B. ANGLE MEASUREMENTS	LASER TRACKING TELESCOPE	GIMBALLED LASER LIGHT SOURCE		B_1 INERTIAL FRAME DEFINED BY STAR SIGHTINGS B_2 LOCAL VERTICAL/ORBIT PLANE REFERENCE DEFINED BY HORIZON SENSOR AND GYROCOMPASSING	B. MEASURE RANGE AND RANGE RATE. • LOW-G ACCELEROMETER • RADAR ALTIMETER	
SPECIAL EARTH TARGETS	TRACKING TELESCOPE MEASURES ANGLES TO EARTH TARGET	GIMBALLED LASER TRANSMITTERS PLACED NEAR ORBIT PATH	EPHEMERIS OF S/C FOR LASER TRANSMITTER POINTING	EITHER OF TWO ATTITUDE REFERENCE FRAMES A. INERTIAL FRAME DEFINED BY STAR SIGHTINGS B. LOCAL VERTICAL/ORBIT PLANE FRAME DEFINED BY HORIZON SENSOR	• RADAR ALTIMETER • LOW-G ACCELEROMETER	III

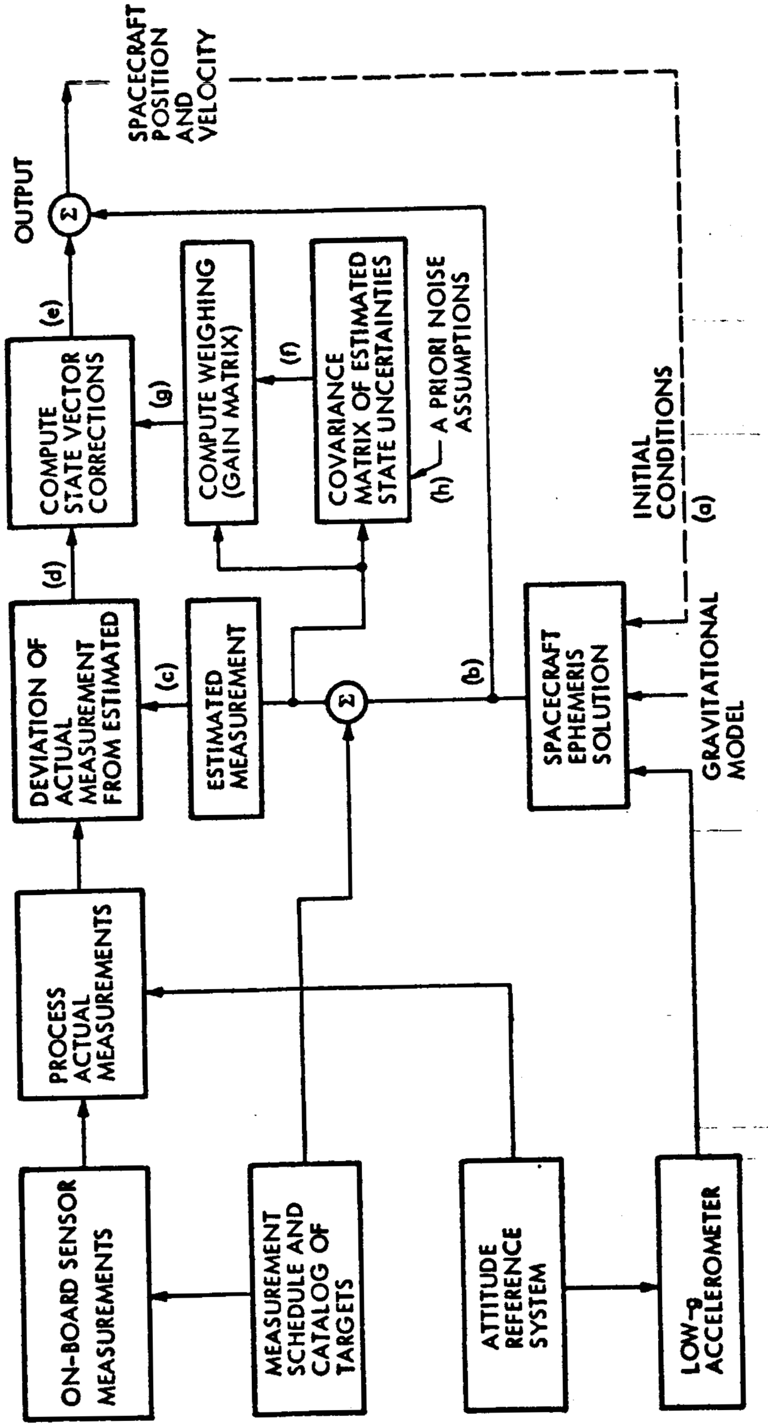

FIG. 10-1 TYPICAL ORBIT NAVIGATION SYSTEM BLOCK DIAGRAM

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

TABLE 10.2
TYPICAL KALMAN EQUATIONS

FILTER EQUATIONS FORM

	Solved-For Parameters	Considered Parameters ($\underline{p}$, $\underline{m}$)
Between Measurements	$\underline{\hat{x}}^*_s = \phi\,\underline{\hat{x}} + P^* P^{-1} G \underline{u} + \underline{f}$ $P' = \phi P \phi^T + Q$	$\underline{\hat{x}}^*_c = \underline{\hat{x}}^*_s + J\,\underline{p}$ $P^*_c = P' + \phi C'_{px} G^T - G C'^{\,T}_{px} \phi^T + GDG^T$

LINEAR SYSTEM EQUATIONS STRUCTURE

$\underline{x}(t_2) = \Phi(t_2, t_1)\,\underline{x}(t_1) - G(t_2, t_1)\,\underline{u} - \underline{f}(t_1) - \underline{g}(t_1)$						$\underline{y}(t_2) = H(t_2)\,\underline{x}(t_2) - \underline{n}(t_2)$
STATE VECTOR COMPONENTS	$\underline{x}(t_1)$	$\phi(t_2, t_1)$	$G(t_2, t_1)$	$\underline{f}(t_1)$	$\underline{g}(t_1)$	$H(t_2)$
6 - orbit state components 6 - attitude state components	$\begin{bmatrix} \underline{x}^o \\ \underline{x}^A \\ g^o_c \end{bmatrix}$	$\begin{bmatrix} \phi^o & \phi^{oA} & 1 & 0 & 0 & 0 & 0^{o\alpha} & 0 & 0 & 0 \\ \phi^{Ao} & \phi^A & 0 & 1 & 0 & 0 & 0 & \phi^{Ad} & 0 & 0 \\ 0 & 0 & \phi^{go} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} G^o \\ G^A \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} \underline{f}^o \\ \underline{f}^A \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ \underline{g}^o_c \\ \underline{a}^A_c \end{bmatrix}$	

NOISE EQUATIONS

	Measurement Noise	Plant Noise
Zero Mean	$E[\underline{n}(t_i)] - 0$	$E[\underline{q}(t_i)]\ \ 0$ for all i

Section 11

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