

APOLLO

GUIDANCE AND NAVIGATION

These papers were presented by the authors at Wiesbaden, Germany and Brussels, Belgium in June of 1965 under the sponsorship of NATO's Advisory Group for Aeronautical Research and Development.

R-500

SPACE NAVIGATION
GUIDANCE AND CONTROL

Volume 2 of 2

JUNE 1965

by Dr. C. S. Draper
Dr. W. Wrigley
D. G. Hoag
Dr. R. H. Battin
J. E. Miller
D. A. Koso
Dr. A. L. Hopkins
Dr. W. E. Vander Velde

MIT

**INSTRUMENTATION
LABORATORY**

CAMBRIDGE 39, MASSACHUSETTS

ACKNOWLEDGMENT

This report was prepared under DSR Project 55-238, sponsored by the Manned Spacecraft Center of the National Aeronautics and Space Administration through Contract NAS 9-4065.

The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

© Copyrighted by the Massachusetts Institute of Technology.
Published by the Instrumentation Laboratory of the
Massachusetts Institute of Technology.
Printed in Cambridge, Massachusetts, U.S.A., 1965

TABLE OF CONTENTS

Volume II of II

Volume I (Separately bound document)

Part I

GUIDANCE - BASIC PRINCIPLES

Dr. C. Stark Draper

Chapter		Page
	INTRODUCTION	I-3
I-1	PROBLEMS OF GUIDANCE	I-5
I-2	GEOMETRICAL ASPECTS OF GUIDANCE AND CONTROL	I-15
I-3	FUNCTIONAL REQUIREMENTS OF SYSTEMS AND THEIR COMPONENTS FOR CONTROL AND GUIDANCE	I-22
I-4	STATE OF TECHNOLOGY OF COMPONENTS FOR CONTROL, NAVIGATION, AND GUIDANCE SYSTEMS	I-37
I-5	GYROSCOPE UNITS FOR REALIZATION OF GUIDANCE SYSTEM REFERENCE COORDINATES	I-42
I-6	BASIC PRINCIPLES OF GYRO UNIT APPLICATIONS	I-60
I-7	SPECIFIC FORCE RECEIVERS	I-65
I-8	INERTIAL SYSTEMS	I-70
	BIBLIOGRAPHY	I-72

Part II

THE NAVIGATION, GUIDANCE, AND CONTROL OF A MANNED LUNAR LANDING

David G. Hoag

II-1	THE BACKGROUND AND THE PROBLEM OF SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL	II-3
II-2	GUIDANCE, NAVIGATION, AND CONTROL TASKS IN THE APOLLO MISSION	II-21
II-3	GUIDANCE, NAVIGATION, AND CONTROL INSTRUMENTATION IN APOLLO	II-45
II-4	OPERATION MODES OF GUIDANCE, NAVIGATION, AND CONTROL APOLLO COMMAND MODULE BLOCK I	II-67
II-5	SPACECRAFT SAFETY CONSIDERATIONS OF GUIDANCE, NAVIGATION, AND CONTROL	II-83

TABLE OF CONTENTS (Continued)

Part III

EXPLICIT AND UNIFIED METHODS OF
SPACECRAFT GUIDANCE
Dr. Richard H. Battin

Chapter		Page
	INTRODUCTION	III-3
III-1	ACCELERATED FLIGHT NAVIGATION	III-5
III-2	COASTING FLIGHT NAVIGATION	III-11
III-3	POWERED-FLIGHT GUIDANCE	III-27
III-4	MID-COURSE GUIDANCE	III-39
	BIBLIOGRAPHY	III-51

Volume II

Part IV

INERTIAL MEASUREMENT UNITS AND PULSE TORQUING
John F. Miller

IV-1	THE APOLLO INERTIAL MEASUREMENT UNIT	IV-3
IV-2	THE PULSED INTEGRATING PENDULOUS ACCELEROMETER (PIPA)	IV-27
IV-3	THE COUPLING DATA UNIT (CDU)	IV-45
	BIBLIOGRAPHY	IV-57

Part V

OPTICAL MEASUREMENTS AND NAVIGATION PHENOMENA
D. Alexander Koso

	INTRODUCTION	V-3
V-1	NAVIGATION IN ORBIT	V-5
V-2	MID-COURSE NAVIGATION	V-25
V-3	THE APOLLO OPTICAL UNIT	V-41
	BIBLIOGRAPHY	V-45

TABLE OF CONTENTS (Continued)

Part VI

GUIDANCE COMPUTER DESIGN
Dr. Albert L. Hopkins, Jr.

Chapter		Page
	INTRODUCTION	VI-3
VI-1	CHARACTERISTICS OF GUIDANCE COMPUTERS	VI-5
VI-2	CHARACTERISTICS OF THE APOLLO GUIDANCE COMPUTER	VI-13
VI-3	MECHANIZED AIDS TO DESIGN AND PRODUCTION	VI-69
VI-4	GROUND SUPPORT EQUIPMENT	VI-79
VI-5	CONCLUSION	VI-81
	BIBLIOGRAPHY	VI-83

Part VII

SPACE VEHICLE FLIGHT CONTROL
Dr. Wallace E. Vander Velde

	INTRODUCTION	VII-3
VII-1	POWERED FLIGHT CONTROL	VII-5
VII-2	COASTING FLIGHT CONTROL	VII-40
VII-3	ATMOSPHERIC FLIGHT CONTROL	VII-51

PREFACE

The material in this book was assembled to support a series of lectures to be given by the authors in Europe in June 1965, under the sponsorship of the Advisory Group for Aerospace Research and Development, an agency of NATO.

The general subject of Space Vehicle Control Systems is the subject of discussion with particular application to the present Manned Lunar Landing Program. The man-machine interaction along with requirements of the mission are first described. These mission requirements in terms of specific hardware along with the performance requirements and underlying reasons for choice are next explained. Lastly, the theoretical background, the system analysis and the derivation of the control functions to integrate the hardware into a precision guidance, navigation and control system are discussed. The book is organized into seven sections following the pattern of the lectures.

Section I provides historical background to the fundamental problems of guidance and navigation. The basic physical phenomenon and associated instrument techniques are discussed.

Section II continues with background information going more specifically into the problems and approach of the guidance, navigation and control of the Apollo manned lunar landing mission. This section illustrates some of the basic philosophy and approaches to the Apollo tasks, such as the success enhancing decision to provide equipment that will perform all necessary operations on-board and using all ground based help when available.

Section III concerns in detail the analytic foundation for performing on-board calculations for navigation and guidance. The achievement of a unified and universal set of equations provides an economy in on-board computer program to perform all the various mission tasks.

Section IV covers in detail the mechanization of the inertial sensor equipment of the Apollo guidance and control system.

Section V provides the same visibility into the optical navigation sensors and measurement techniques.

Section VI provides background and specific techniques in the mechanization of on-board digital computers. Application to the Apollo mission illustrates several problems of interest such as the method for providing reasonable and straightforward astronaut data input and readout.

Section VII concerns the specific problems and solutions of vehicle attitude control under conditions both of rocket powered flight and the free-fall coast conditions. The Apollo mission provides a diversity of examples of this area of technology in the control schemes of the command and service module, the lunar landing vehicle, and the earth entry return configuration.

The general problems of Space Navigation, Guidance, and Control requires a great variety of discipline from the engineering and scientific fields. The successful completion of any one space mission or phase of a space mission requires a team effort with a unified approach. Of equal importance are the software deliveries and performance with the hardware. This lecture series is an attempt to integrate many of the disciplines involved in creating successful and accurate space vehicle control systems.

These lectures represent, on every ones part, an interplay between equipment and theory. While in each case emphasis may be on one or the other, in the whole equal emphasis is applied.

All sections may be treated as separate entities however in the case of Section III through VII it is helpful to have the background of Section II. There is cross reference between sections to avoid unnecessary duplication.

It is observed that the authors have emphasized the Apollo mission and hardware as examples in their treatment of the subjects. This is partially because of their intimate familiarity with Apollo in the development work at the Instrumentation Laboratory of MIT and partially because Apollo provides, in an existing program, an excellent example in its multiple requirements and diversity of problems. Because Apollo is currently under development, no particular attempt has been made to make reference only to the latest configuration details. Indeed the authors have utilized various stages of the Apollo development cycle without specific identification in every case as they provide the guidance, navigation, or control technique example desired.

The authors wish to express their appreciation to NASA for the opportunity to participate in the lecture series and for permission to use material from the research and development contracts NAS 9-153 and NAS 9-4065. They also recognize that this does not constitute approval by NASA of this material. In addition, they wish to thank the many members of M. I. T. 's Instrumentation Laboratory; who are working on the Apollo system, for their inspiration and generation of material.