Spacecraft Systems Engineering

Fourth Edition

Editors

Peter Fortescue | Graham Swinerd | John Stark



SPACECRAFT SYSTEMS ENGINEERING

SPACECRAFT SYSTEMS ENGINEERING

Fourth Edition

Edited by

Peter Fortescue

University of Southampton, UK

Graham Swinerd

University of Southampton, UK

John Stark

Queen Mary, University of London, UK



This edition first published 2011 © 2011, John Wiley & Sons, Ltd

First Edition published in 1991, Second Edition published in 1995, Third Edition published in 2003

Registered office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data

Spacecraft systems engineering / edited by Peter Fortescue, Graham Swinerd, John Stark.—4th ed. p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-75012-4 (hardback)

- 1. Space vehicles—Design and construction. 2. Astronautics—Systems engineering.
- I. Fortescue, Peter W. II. Swinerd, Graham. III. Stark, John.

TL875.S68 2011 629.47'4—dc22

2011015486

A catalogue record for this book is available from the British Library.

Print ISBN: 9780470750124 ePDF ISBN: 9781119971016 oBook ISBN: 9781119971009 ePub ISBN: 9781119978367 Mobi ISBN: 9781119978374

Set in 10/12pt Times by Laserwords Private Limited, Chennai, India.

Dedicated to the memory of Nicky Skinner 1978–2011

CONTENTS

List	t of C	ontributors	xiii		
Pre	face	to the Fourth Edition	XV		
	Preface to the Third Edition				
Pre	face	to the Second Edition	xxi		
Pre	face	to the First Edition	xxiii		
Lis	t of A	cronyms	XXV		
1	INT	RODUCTION			
	Joh	n P. W. Stark, Graham G. Swinerd and Adrian R. L. Tatnall			
	1.1	Payloads and Missions	3		
	1.2	A System View of Spacecraft	4		
	1.3	The Future	9		
2		SPACECRAFT ENVIRONMENT AND ITS EFFECT ON DESIGN			
	Joh	n P. W. Stark			
	2.1	Introduction	11		
	2.2	Pre-Operational Spacecraft Environments	11		
	2.3	Operational Spacecraft Environments	17		
	2.4	Environmental Effects on Design	40		
3		NAMICS OF SPACECRAFT			
	Pete	er W. Fortescue and Graham G. Swinerd			
	3.1	Introduction	49		
	3.2	Trajectory Dynamics	51		
	3.3	General Attitude Dynamics	58		
	3.4	Attitude Motion of Specific Types of Spacecraft	63		
	3.5	Oscillatory Modes	71		
	3.6	In Conclusion	73		
	Appe	endix: The Inertia Matrix	73		
4	CEL	ESTIAL MECHANICS			
	Joh	n P. W. Stark, Graham G. Swinerd and Peter W. Fortescue			
	4.1	Introduction	79		
	4.2	The Two-body Problem—Particle Dynamics	81		
	4.3	Specifying the Orbit	92		
	4.4	Orbit Perturbations	93		

viii *CONTENTS*

	4.5	Restricted Three-body Problem	106
5		SION ANALYSIS	
	Johi	n P. W. Stark and Graham G. Swinerd	
	5.1	Introduction	111
	5.2	Keplerian Orbit Transfers	114
	5.3	Mission Analysis	116
	5.4	Polar LEO/Remote-Sensing Satellites	122
	5.5	Satellite Constellations	127
	5.6	Geostationary Earth Orbits (GEO)	133
	5.7	Highly Elliptic Orbits	143
	5.8	Interplanetary Missions	147
6		PULSION SYSTEMS	
	J. Ba	arrie Moss and John P. W. Stark	
	6.1	Systems Classification	177
	6.2	Chemical Rockets	180
	6.3	Spacecraft Propulsion	202
	6.4	Electric Propulsion	206
7	LAU	NCH VEHICLES	
	J. Ba	arrie Moss and Graham E. Dorrington	
	7.1	Introduction	221
	7.2	Basic Launch Vehicle Performance and Operation	222
	7.3	Spacecraft Launch Phases and Mission Planning	231
	7.4	The Ariane 5 Launch Vehicle	236
	7.5	US Crewed Launch Systems	239
	7.6	Small Launchers and Reusable Sub-Orbital Vehicles	242
	7.7	Re-Entry into Earth's Atmosphere	244
	7.8	Specific Launch Costs and Reliability	247
8	SPA	CECRAFT STRUCTURES	
		n M. Houghton	
	8.1	Introduction	251
	8.2	Design Requirements	251
	8.3	Material Selection	256
	8.4	Analysis	263
	8.5	Design Verification	274
	8.6	Impact Protection	276
	8.7	Configuration Examples	278
	8.8	The Future of Space Structures	285
9		ITUDE CONTROL	
	Pete	er W. Fortescue and Graham G. Swinerd	
	9.1	Introduction	289
	9.2	ACS Overview	290

CONTENTS	11/
	IX

	9.3	The Spacecraft Attitude Response	294
	9.4	Torques and Torquers	301
	9.5	Attitude Measurement	309
	9.6	ACS Computation	321
10		CTRICAL POWER SYSTEMS	
	John	P. W. Stark	
	10.1	Introduction	327
	10.2	Power System Elements	328
	10.3	Primary Power Systems	330
	10.4	Secondary Power Systems: Batteries	345
	10.5	Power Management, Distribution and Control	347
	10.6	Power Budget	350
11		RMAL CONTROL OF SPACECRAFT	
		S.J. Savage	
	11.1	Introduction	357
	11.2	The Thermal Environment	358
	11.3	Thermal Balance	362
	11.4	Thermal Analysis	366
	11.5	Thermal Design	371
	11.6	Thermal Technology	375
	11.7	Thermal Design Verification	386
	11.8	Example of Satellite Thermal Design—XMM/Newton	390
12		COMMUNICATIONS	
	Ray I	E. Sheriff and Adrian R. L. Tatnall	
	12.1	Introduction	395
	12.2	Techniques of Radio Communications	400
	12.3	The Communications Payload	422
	12.4	Conclusion	436
13		METRY, COMMAND, DATA HANDLING AND PROCESSING	
	•	I P. Fillery and David Stanton	400
	13.1	Introduction	439
	13.2	System Architecture	440
	13.3	Telemetry Data Formatting	442
	13.4	Telecommand	449
	13.5	Communication Techniques and Protocols	455
	13.6	On-Board Data Handling (OBDH) and Processing	458
	13.7	Technology	464
	13.8	Tools and Controlling Documents	466
14		UND SEGMENT ck Chatel	
	14.1	Introduction	467
	1 (. 1	madadada	407

x CONTENTS

	14.2	The Ground Station	468
	14.3	Flight Dynamics	475
		The Ground Data System	480
		The Flight Operations System	483
16	CDA	CECRAFT MECHANISMS	
15		ielmo S. Aglietti	
	15.1	Introduction	495
	15.1	One-Shot Devices	495
	15.2		507
	15.4	Continuously and Intermittently Operating Devices	513
	15.4	Components Materials	
			520
		Tribology	521
		Testing and Verification	523
	15.8	Conclusion	524
16	SPA	CECRAFT ELECTROMAGNETIC COMPATIBILITY ENGINEERING	
	Ken I	M. Redford	
	16.1	Introduction	527
		Examples of EMC Problems	528
	16.3	EMC Specifications	528
	16.4	Electromagnetic Compatibility—Terms and Definitions	529
	16.5	EMC Fundamentals	530
	16.6	The Systems Approach to EMC	531
		EMC Categories	531
	16.8	Electrostatic Discharge	535
	16.9	Spacecraft Grounding Schemes	536
		Major Causes of Spacecraft EMC Problems	541
	16.11	Analysis Methods for Spacecraft EMC Engineering	542
17	ASS	EMBLY, INTEGRATION AND VERIFICATION	
		Ransome	
	17.1	Introduction	545
	17.2	Some Definitions	545
	17.3	The Verification Plan	547
	17.4	Relationship between Analysis and Test	551
	17.5	The AIV Plan	552
	17.6	Testing: General	553
	17.7	Test Types	557
	17.8	Model Philosophy	561
	17.9	Build Standards and Applications	564
		Ground Support Equipment	567
		Checkpoints in the AIV Programme	571
		Verification Closeout	572
		Launch Preparation	572
		Conclusion	573

CONTENTS xi

18	SMA	LL SATELLITE ENGINEERING AND APPLICATIONS	
	Marti	in N. Sweeting and Craig I. Underwood	
	18.1	Introduction	575
	18.2	Small Satellite Design Philosophy	579
	18.3	Small Satellite System Design	580
	18.4	COTS Components in the Space Environment	583
	18.5	Microsatellite Platforms	587
	18.6	Minisatellite Platforms	590
	18.7	Nanosatellite Platforms	590
	18.8	Affordable Launches for Small Satellites	592
	18.9	In-Orbit Operations	594
	18.10	Small Satellite Applications	597
	18.11	Picosatellites and Recent Advances in Miniaturization	603
	18.12	Conclusion	604
19		DUCT ASSURANCE	
	Geoff	frey Hall	
	19.1	Introduction	607
	19.2	Product Assurance in a Project	609
	19.3	Reliability/Dependability	613
	19.4	Parts	618
	19.5	Materials and Processes	622
	19.6	Product Assurance in Manufacturing, AI&V	626
	19.7	Safety	634
	19.8	Product Assurance in Operations	637
		Software Product Assurance	638
		PA in Technology Developments	640
	19.11	The Assurance Message	642
20		CECRAFT SYSTEM ENGINEERING	
	Adria	n R. L. Tatnall, John B. Farrow, Massimo Bandecchi and C. Richard Francis	
	20.1	Introduction	643
	20.2	System Engineering	644
		Concurrent Engineering	654
		A Case Study: Cryosat	667
	20.5	Conclusion	678
Ind	ex		679

LIST OF CONTRIBUTORS

EDITORS

Peter W. Fortescue

Aeronautics and Astronautics, Faculty of Engineering and the Environment, University of Southampton, UK (retired)

Graham G. Swinerd

Aeronautics and Astronautics, Faculty of Engineering and the Environment, University of Southampton, UK

John P. W. Stark

School of Engineering and Materials Science, Queen Mary, University of London, UK

AUTHORS

Guglielmo S. Aglietti

Aeronautics and Astronautics, Faculty of Engineering and the Environment, University of Southampton, UK

Massimo Bandecchi

European Space Research and Technology Centre (ESTEC), European Space Agency, The Netherlands

Franck Chatel

German Space Operations Center (GSOC), Oberpfaffenhofen, Germany

Graham E. Dorrington

School of Engineering and Materials Science, Queen Mary, University of London, UK

John B. Farrow

International Space University, Strasbourg, France

Nigel P. Fillery

EADS Astrium, Portsmouth, UK

C. Richard Francis

European Space Research and Technology Centre (ESTEC), European Space Agency, The Netherlands

Geoffrey Hall

Moreton Hall Associates, Maidenhead, UK

John M. Houghton

EADS Astrium, Stevenage, UK

J. Barrie Moss

School of Engineering, Cranfield University, UK

Terry Ransome

EADS Astrium, Stevenage, UK

Ken M. Redford

British Aerospace, Bristol, UK

Chris J. Savage

European Space Research and Technology Centre (ESTEC), European Space Agency, The Netherlands (retired)

Ray E. Sheriff

School of Engineering, Design and Technology, University of Bradford, UK

David Stanton

Keltik Ltd, Hampton Hill, UK

Martin N. Sweeting

Surrey Space Centre, University of Surrey, Guildford, Surrey, UK

Adrian R. L. Tatnall

Aeronautics and Astronautics, Faculty of Engineering and the Environment, University of Southampton, UK

Craig I. Underwood

Surrey Space Centre, University of Surrey, Guildford, Surrey, UK

PREFACE TO THE FOURTH EDITION

When I was thinking about what to say in this foreword to the fourth edition, I had a look back over the previous editions to get a flavour of what was going on when they were published—the first two decades ago! Obviously a great deal has changed in that time, which is of course reflected in the current book's content. However, one aspect that has remained constant throughout that time is the influence that the US Space Shuttle has had as the work-horse of the West's human spaceflight programme.

The Shuttle's first launch three decades ago, in 1981, was for me one of those landmark events that somehow spurs the memory to recall exactly where you were and what you were doing at the time. For me, the 12th of April 1981 was a glorious spring day, during which my wife and I enjoyed the climb of a peak in the remote north-west Highlands of Scotland. However, sensing the historic character of the day's events, I do recall a resolve at the end of that glorious day to find out how the first historic flight of Shuttle Columbia had gone. The subsequent history of the Shuttle programme is well documented. Despite the high cost of operations, the programme has overall been hugely successful, but also overshadowed by the human cost of desperate tragedies. Coming full circle, this year sees the retirement of this remarkable machine, again an event with a personal dimension—the commencement and retirement of the Shuttle's space career have coincided closely with my own career in the space industry and academia! Consequently, like an old friend, it's always been there.

The Shuttle retirement has inevitably forced a rethink of the US human spaceflight programme. As a consequence, the Bush administration proposed the Constellation programme which centred on a new crewed spacecraft Orion. This was to be lifted to orbit by the Shuttle replacement—the man-rated Ares 1 launcher. The other significant component of the programme was a heavy-lift launch vehicle called Ares 5, which would independently orbit the massive payloads required for human exploration beyond Earth orbit. The main objectives of the programme were a return to the moon by 2020, and preparations for a crewed landing on Mars in the longer term. However, the incoming Obama administration has effectively overturned the 'Bush vision', throwing open the development of human access to orbit to private venture, abandoning the immediate prospect of human exploration beyond Earth orbit, and extending the lifetime of the International Space Station to 2020. In the short-term this has led to the rather bizarre situation of focusing US human spaceflight activities on Earth orbit, but without the independent means of US astronauts to reach it. At the time of writing, the future development of US human spaceflight is unclear, which raises the prospect that the next footprints on the moon's surface may be those of Chinese taikonauts. As far as the book content is concerned,

this has not been a good time to attempt to write about this aspect of space activity. For example, reference to the Space Shuttle is minimal throughout the current edition, and the emphasis in the launch vehicles section (Chapter 7) is on the European Ariane launcher programme (although there is some discussion of the Ares launchers, which in the fullness of time may, or may not, be relevant).

The majority of the book content, however, focuses on the design and engineering of unmanned spacecraft, and around the turn of the millennium, the 'faster, better, cheaper' design philosophy was particularly influential in reducing the size and mass of science spacecraft in particular. However, this has been tempered somewhat by the occurrence of inopportune in-orbit failures, which have provided lessons that maybe faster and cheaper are not necessarily better. However, the explosion of interest in small, capable spacecraft continues unabated, and this is reflected in an updated Chapter 18 on small satellite engineering.

At the other end of the size range, there are a number of major robotic spacecraft programmes that will be making the headlines soon after this edition hits the book shelves. Perhaps, the most significant of these is the follow-on to the Hubble Space Telescope, which has been christened the James Webb Space Telescope. This is to be launched in around 2014 to the L₂ Sun-Earth Lagrange point, around 1.5 million km from Earth. With a mirror nearly three times the size of Hubble's, the scientists are looking forward to an explosion of new cosmological discoveries resulting from its operation. At the same time, the ESA comet probe Rosetta should be beginning its mission in orbit around comet 67P/Churyumov-Gerasimenko, and it is anticipated that the Rosetta data will provide a step function in our understanding of the origins of our local environment, the solar system. In the world of application satellites, a new global navigation satellite system called Galileo should become operational, also around 2014. This is a civil programme, funded by the European Union, involving the launch of a constellation of 30 satellites in Earth orbits at a height of around 23 000 km. It is hoped that the introduction of this non-military system will remove the reticence of civilian organisations to embrace the technology of satellite navigation in their operations. One significant development arising from this is the prospect of satellite navigation being fully utilized in the arena of civil air traffic control.

This fourth edition of Spacecraft Systems Engineering has been significantly revised and updated throughout, so that readers can master the many facets involved in an unmanned space vehicle project, like those mentioned above, from early system design through to in-orbit flight operations. There are also some 'all-new' features which are worthy of additional mention. Current trends in interplanetary missions have suggested that a new section on low-thrust trajectories would be helpful, and this has been added to the alreadyextensive Mission Analysis chapter (Chapter 5). The previous Chapter 14 on Ground Stations has been rewritten. The new version has been entitled 'Ground Segment' to emphasize that this area is not just about ground station aspects, but also includes many other activities such as flight operations. A new chapter (Chapter 17) has been added devoted to the important topic of Assembly, Integration and Verification, which focuses on the later stages of a spacecraft project when the whole system is brought together and tested prior to launch. The old chapter on Product Assurance has been completely rewritten (Chapter 19) to reflect the diverse aspects of PA, including that of software. This is particularly pertinent in the space sector, in which the manufactured 'products' often must survive many years in a hostile environment without the benefit of maintenance.

The final chapter on Spacecraft System Engineering (Chapter 20) has also been rewritten, changing the emphasis to discuss system design methods—in particular that of concurrent engineering design. System design in action is illustrated by discussion of the design development of the ESA Cryosat spacecraft, which is used as a case study.

Finally, the editors wish to thank the army of contributors who have given their time and effort to bring this edition to fruition—without them a new edition would not have been possible. We are also indebted to the team at Wiley, in particular to Nicky Skinner and Gill Whitley, whose assistance throughout the period of compilation of the manuscript was invaluable. As this stage was drawing to a close, and the production process was beginning, we were shocked and saddened by the sudden death of Nicky Skinner in March. My regret is that our working relationship was conducted purely by email as is often the case these days. Although I did not have an opportunity to meet up and consolidate that relationship, nevertheless I feel I got to know Nicky very well. I am thankful for her assistance throughout, and it is entirely appropriate that this edition is dedicated to her memory.

Graham SwinerdSouthampton, March 2011

PREFACE TO THE THIRD EDITION

Graham Swinerd, my friend and colleague, took over the running of the Space Technology short courses at Southampton University when I retired in 1989. Who would be a better choice than Graham to take over the role of principal editor for this new edition of Spacecraft Systems Engineering? I am sure that Graham will build on the reputation that the past editions have achieved, and I wish him success in his new role. Over to you, Graham...

Peter Fortescue, Southampton, July 2002

Since the publication of the previous edition, Dan Goldin's 'Faster, Better, Cheaper' space mission philosophy has had a major impact upon American activities. As a consequence, the last of the heavyweight interplanetary spacecraft, Cassini, was launched in October 1997 on its mission to Saturn. Programmes such as NEAR Shoemaker, which launched a relatively small but capable spacecraft in February 1996 to orbit and ultimately to land on a small body—the asteroid 433 Eros—have substituted this type of mission. These 'small missions' have significantly influenced current and proposed planetary exploration programmes.

In the same interim period, we have also seen the launch of constellations into low Earth orbit, for global mobile communications using handheld telephones—in particular, the Iridium constellation, the first satellites of which were lofted in May 1997. Although financial problems have impacted this programme, it nevertheless heralds large-scale use of constellation systems in many application areas. There are great benefits to the usage of these distributed systems, not only in communications and navigation applications but also in improving the temporal coverage of Earth observation. There is also an implicit trend here to use a number of small, but capable, spacecraft to do the job of one or two large satellites.

The principal driver for the development of small satellite technology is the reduction in cost associated with access to space. The elements contributing to this philosophy are low launch costs, a short design, build and test period, a less complex ground interface and operations, and the recognition of a means of testing new spacecraft technologies in a relatively low financial risk environment.

At the other end of the size spectrum, December 1998 saw the first elements of the International Space Station (ISS) being brought together in orbit. If development continues

as originally planned, around 2005, the ISS will become the largest structure (\sim 400 tonnes) ever to be deployed in Earth orbit, marking the beginning of permanent habitation in space.

These various developments have had a significant influence on the structure of the new edition of the book. The major changes involve the removal of the chapter on atmospheric re-entry, and the addition of a new chapter on small satellite engineering and applications. Much of the removed material has been redistributed in other chapters, however, for example, Earth atmosphere re-entry is included in Chapter 7 (Launch Vehicles), and sections on aero-manoeuvring have been included in Chapter 5 (Mission Analysis). The new Chapter 18 on Small Satellites has been contributed by Martin Sweeting and Craig Underwood of the Surrey Space Centre, based at the University of Surrey, UK. Both individuals are recognized internationally for their expertise in this field. The chapter, built on the huge expertise of the Surrey Space Centre, gives insights into small satellite systems engineering in general. Given the growing activity in this area, no textbook of this kind is complete without such a contribution.

Other chapters have been rewritten—in particular, Chapter 8 (Spacecraft Structures), Chapter 11 (Thermal Control), Chapter 16 (Electromagnetic Compatibility) and Chapter 19 (Spacecraft Systems Engineering)—and most of the others have been substantially revised, including a discussion of constellation design and small-body missions in Chapter 5 (Mission Analysis).

Some of the authors of the second edition have retired, and new names have appeared in the contributors list. The editors are grateful to all of them for their contributions. It is also sad to report that three of our previous authors have died in the interim—Howard Smith (Telecommunications), Les Woolliscroft (Spacecraft Electromagnetic Compatibility Engineering) and Mervyn Briscoe (Spacecraft Mechanisms). Each of them will be sadly missed.

The reader may have noticed the dedication at the front of the book to one of these authors, Mervyn Briscoe, who was actively involved in revising his chapter on Mechanisms when he died in 2001. Our thanks are also due to Guglielmo Aglietti who jumped into the hot seat to complete the revision of Mervyn's chapter as a co-author. Mervyn gave loyal service as a contributor to the short course activity at Southampton over many years, and we would like to acknowledge this by dedicating this edition to his memory.

Finally, it is appropriate to thank both Peter Fortescue and John Stark for their pioneering work in bringing the previous editions to fruition, and for their valued assistance with this one.

Graham SwinerdSouthampton, July 2002

PREFACE TO THE SECOND EDITION

This second edition comes in response to a phone call that we editors had been dreading. 'Had we thought of producing a second edition?' After much consideration our answer was 'Yes', and here it is.

Not only has it given our contributing authors a chance to update the material in their chapters—the technology is developing all the time and five years is a long time! It has also given us the opportunity to rectify some of the errors in the first edition (and possibly to introduce some new ones), and to respond to suggestions from readers about the content and to our inevitable 'second thoughts' on the matter. As a result there are two new chapters.

The first is on Mechanisms—important equipment on spacecraft. They are an essential part of many of the systems that are covered in the other chapters, but having their own requirements we have given them chapter status here. They are a specialist topic, involving the problem of moving one mechanical part relative to another. For an application that has a long life, no servicing, no disturbance to the structure, and ideally no single point failure as design objectives, mechanism designers are faced with a challenging task. Chapter 16 tells us how they have responded to it.

The second additional chapter addresses the subject of System Engineering. The first edition has no hyphens in its title. Those who read the title as meaning 'The Engineering of Spacecraft Systems' will probably have found that the content was much as they had expected. Indeed there have been enough satisfied readers to cause the dreaded question of a second edition to be raised. However, it could also be read as meaning 'Systems Engineering of Spacecraft', and those who interpreted it as such will no doubt have been disappointed to have found little on the discipline of System Engineering in the book.

So our response is to retain the same ambiguous title, and to retain the same thrust as in the first edition. But we have added a new chapter (No. 19), which focuses on the subject of Systems Engineering of spacecraft. It is written by authors within the spacecraft industry who have experience in that activity. We hope it will bring together the pieces of the jigsaw puzzle that are to be found among the other chapters, and will show how they can be fitted together harmoniously to form a viable whole—a spacecraft that meets its design objectives in a viable manner.

Since the first edition some of our authors have moved to new locations; some have retired. New names have appeared in our list of contributors. We editors are grateful to them all—new and old—and trust that this edition presents 'second thoughts' that are an improvement on the first.

PREFACE TO THE FIRST EDITION

This book has grown out of a set of course notes, which accompany a series of short courses given at Southampton University. These courses started in 1974 with a two week 'space technology' course, and they are aimed at the recent science or engineering graduate who wishes to become a spacecraft engineer. The courses are still thriving, now serving much of European industry, with one-week versions for experienced engineers, sometimes senior ones, who are specialists in their own fields.

On the courses, the attendees work in competing teams on a project that involves designing a spacecraft in response to an overall objective. Over the years, mission designs have been directed at all application areas: science, astronomy, communications and Earth observations. There is now a 'museum' of models that demonstrate vehicle layouts and support the attendees' presentations covering operation, subsystem specification and launch constraints. These models demonstrate system viability rather than detailed design. The projects are designed at 'system level', and their supervision has provided a basis for deciding the level of detail that should be included in this book.

The coverage in this book is therefore aimed at giving the breadth that is needed by system engineers, with an emphasis on the bus aspect rather than on the payload. The specialist engineer is well served with textbooks, which cover many of the subsystems in detail and in depth. He is unlikely to learn very much about his own specialist topic from this book. But he may well learn something about other specialists' disciplines, and, it is hoped, enough for him to appreciate the trade-offs that affect his own subsystem in relation to others.

Chapters 2 to 5 set the general scene for spacecraft, and particularly for satellites. They must operate in an environment that is generally hostile compared to that with which we are familiar on Earth, and the main features of this are described in Chapter 2. Chapters 3 and 4 address the dynamics of objects in space, where the vehicles will respond to forces and moments that are minute, and which would be discounted as of no significance if they occurred on Earth. Indeed, most of them do occur here, but we do not often operate in a fully free state, and our Earth-bound vehicles are subject to other, much larger forces.

Chapter 5 relates the motion of the spacecraft to Earth rather than to the inertially based reference system of celestial mechanics.

Chapters 6 to 15 address the main subsystems. Chapters 7 and 8 cover the subjects of getting off the ground and returning through the atmosphere. Chapters 6, 9 to 12 and 14 deal with the main subsystems on board the spacecraft, that include the on-board end of the telemetry and control link (Chapter 14) with ground control (Chapter 15). The communication link is covered in Chapter 13 in which the fundamentals of the subject

are included together with their rather special application to spacecraft. This is relevant to the telemetry and control link and to a communications payload.

Chapter 16 introduces electromagnetic compatibility (EMC), one of the subjects that must be addressed by the systems engineer if the various subsystems are to work in harmony. Product assurance is of vital concern to spacecraft engineers. Their product(s) must survive a hostile launch environment and then must last many years without the luxury of any maintenance. It does great credit to the discipline they exercise, that so many of their products do so.

We editors would like to express our thanks to the authors who have contributed chapters in the book. Most of them have lectured on the courses mentioned above. Our task has been to whittle down the material they have provided since they have been very generous. We are grateful too for their patience. The conversion of course notes into a book was expected to be a short process. How wrong we were!

We would also like to thank colleagues Graham Swinerd and Adrian Tatnall, who read some of the texts and gave advice. And finally our thanks to Sally Mulford, who has converted some much-abused text into typescript with patience and good humour.

LIST OF ACRONYMS

AATSR	Advanced Along-Track Scanning Radiometer	AQAP	Allied Quality Assurance Publication
ABM	Apogee Boost Motor	ARQ	Automatic report queuing
AC	Alternating current	ASAP	Ariane Structure for
ACS	Attitude Control System	ASAI	Auxiliary Payloads
ACU	Antenna Control Unit	ASAR	Advanced Synthetic
A/D	Analogue to digital	ASAK	Aperture Radar
ADEOS	Advanced Earth Observing	ASIC	Application-specific
ADEOS	System		integrated circuit
ADR	Active Debris Removal	ASK	Amplitude-shift keying
AFT	Abbreviated Functional Test	ASS	Antenna Support Structure
AGC	Automatic gain control	ASW	Address and
AIT	Assembly, integration and		synchronization word
	test	ATCS	Active Thermal Control
AIV	Assembly, integration and		System
	verification	ATSR	Along-track Scanning
AKM	Apogee Kick Motor		Radiometer
AM	Amplitude modulation	AU	Astronomical Unit (mean
AMI	Active Microwave		distance from Earth to
	Instrument		Sun)
AMOOS	Aero-Manoeuvring	BCDT	Binary code data transfer
	Orbit-to-Orbit Shuttle	BCH	Bose-Chaudhuri-
AO	Announcement of		Hocquenchem
	Opportunity	BCR	Battery Charge Regulator
AOCS	Attitude and Orbit Control	BDR	Battery Discharge
	System		Regulator
AOP	Announcement of	BER	Bit error rate
	Opportunity Package	BMDO	Ballistic Missile Defence
AOS	Acquisition of signal, also		Organization
	Advanced Orbiting	BMU	Battery Management Unit
	Systems	BOL	Beginning of life
AOTV	Aero-assisted Orbital	BPF	Band-pass filter
	Transfer Vehicle	BPSK	Bi-phase-shift keying
APM	Antenna Pointing	BRTS	Bilateration Ranging
	Mechanism, also		Transponder System
	Attached Pressurized	BSF	Back-Surface Field
	Module	BSR	Back-Surface Reflector
APS	Active Pixel Sensor	CA	Contingency Analysis
			. G J J

CAD	Computer Aided Design	COTS	Commercial off the shelf
CADU	Channel Access Data Unit	CPL	Capillary-pumped loop
CAM	Civil, Aircraft, Military	CPM	Coarse pointing mechanism
CCB	Configuration Control	CR	Corrosion resistance
ССБ	Board		
CCD		CRP	Contingency Recovery
CCD	Charge coupled device		Procedure
CCIR	Comité Consultatif	CSG	Centre Spatial Guyanais
	International de	CTM	Collapsible Tube Mast
	Radiocommunication	CVCM	Collected volatile
CCITT	Comité Consultatif		condensable materials
00111	International de	CW	Continuous-wave
	Téléphonie et de	DARPA	Defence Advanced Research
		DAKIA	
2222	Télégraphie		Project Agency
CCSDS	Consultative Committee for	DB	Data Base
	Space Data Systems	DC	Direct current
CCU	Central Communications	DCP	Data Collection Platform
	Unit	DoD	Department of Defence
CDF	Concurrent Design Facility		(USA)
C&DH	Control and Data Handling	DLR	(German Aerospace Centre)
C&DM	Configuration and Data	DM DM	Development Model
Cadwi			Degree of freedom
CDM	Management	DOF	2
CDMA	Code-division multiple	DORIS	Determination of Orbit and
	access		Radiopositioning
CDR	Critical Design Review		Integrated by Satellite
CE	Concurrent Engineering	DPL	Declared Parts List
CEV	Command Execution	DPSK	Differential phase-shift
	Verification		keying
CFDP	CCSDS File Delivery	DRS	Data Relay Satellite
CIDI	Protocol	DSBSC	Double side-band
CEDD		DSDSC	
CFRP	Carbon fibre reinforced		suppressed carrier
	plastic		modulation
CHAMP	CHAllenging Minisatellite	DS-CDMA	Direct Sequence Code
	Payload		Division Multiple Access
CHRIS	Compact High Resolution	DSN	Deep Space Network
	Imaging Spectrometer	DSP	Digital signal processing,
CIS	Confederation of		also Digital Signal
010	Independent States		Processor
CLA	Coupled loads analysis	ECR	Engineering Change
		LCK	
CLTU	Command Link Transfer	T 000	Request
	Unit	ECSS	European Cooperation for
CMG	Control moment gyroscope		Space Standardization
CMOS	Complementary metal oxide	EDA	Electrically Despun
	semiconductor		Antenna
CNES	Centre National d'Etudes	EDAC	Error detection and
	Spatiales (French	-	correction
	National Space Agency)	EEE	Electrical, Electronic and
COMSAT		LLL	
COMSAT	Communications Satellite		Electromechanical

EGSE	Electrical Ground Support Equipment	FEA FEEP	Finite element analysis Field emission electric
EIRP	Equivalent isotropic radiated	FEM	propulsion Flight Engineering Model
ELV	power	FET	Field effect transistor
	Expendable Launch Vehicle	FFSK	
EM	Electrical Model, also		Fast frequency-shift keying
EMC	Engineering Model	FGSE	Fluids Ground Support
EMC	Electromagnetic	PIPO	Equipment
	compatibility	FIFO	First-In-First-Out
EMI	Electromagnetic interference	FIRST	Far Infra-Red Space
EMP	Electromagnetic pulse		Telescope
EOEP	Earth Observation Envelope	FITS	Failures per 10 ⁹ hours
	Programme	FM	Flight Model, also
EOL	End of lifetime		Frequency Modulation
EOS	Earth Observing System	FMECA	Failure Mode Effects and
e.p.	Equivalent particle		Criticality Analysis
ER-MIL	Established Reliability-MIL	FOG	Fibre optic gyroscope
ERS	Earth Resources Satellite	FOP	Flight Operations
ERT	Earth Received Time		Procedure
ESA	European Space Agency	f.o.r.	Frame of reference
ESATAN	European Space Agency	FOV	Field of view
	Network Analyser	FPGA	Field Programmable Gate
ESD	Electrostatic discharge	11 011	Array
ESOC	European Space Operations	FPM	Fine Pointing Mechanism,
2500	Centre	11111	also Fine-pointing mode
ESTEC	European Space Research	FRB	Failure Review Board
LUILE	and Technology Centre	FRR	Flight Readiness Review
ESTL	European Space Tribology	FRSI	Flexible reusable surface
LOIL	Laboratory	TKSI	insulation
EUMET-	European Meteorological	EC	
SAT		FS	Fail safe
	Satellite Organization	FSK	Frequency-shift keying
EURECA	European Retrievable	FTA	Fault Tree Analysis
ELIMEI	Carrier	GEM	Giotto Extended Mission
EUTEL-	European	GEO	Geostationary Earth orbit
SAT	Telecommunications	GLONASS	Global Navigation Satellite
	Satellite Organization		System
EVA	Extra-vehicular activity	GMT	Greenwich Mean Time
EWSK	East-West Station Keeping	GNSS	Global Navigation Satellite
FAR	Flight Acceptance Review		System
FBC	Faster, Better, Cheaper	GOCE	Gravity field and steady
FCP	Flight Control Procedure		state Ocean Circulation
FDIR	Fault detection, inspection		Explorer
	and recovery	GOES	Geostationary Orbit
FDMA	Frequency-division multiple		Environmental Satellites
	access	GOMOS	Global ozone monitoring by
FE	Finite element		the occultation of stars
		GPS	Global Positioning System

GRACE	Gravity Recovery And	IPN	Interplanetary Internet
UKACE	Climate Experiment	IPNRG	IPN Research Group
GRO	Gamma Ray Observation	IQ	In-phase and Quadrature
GSE	Ground Support Equipment	IRAS	Infra-Red Astronomical
GSFC	Goddard Space Flight	IKAS	Satellite
OSI C	Center	IRIG	Inter-Range Instrumentation
GSOC	German Space Operations	IKIO	Group
doce	Centre	IRTF	Internet Research Task
G/T	Ground track	IKII	Force
GTO	Geostationary transfer orbit	ISC	Integrated System Check
HEO	Highly elliptical orbit	ISDN	Integrated Services Digital
HGA	High Gain Antenna	10011	Network
HGAS	High Gain Antenna System	ISO	Infrared Space Observatory,
HOTOL	Horizontal take-off and	15 0	also International
110102	landing		Organization for
HPA	High power amplifier		Standardization
HRG	Hemispherical Resonator	ISS	International Space Station
	Gyroscope	IST	Integrated System Test
HRSI	High-temperature reusable	IT	Information Technology
	surface insulation	ITU	International
HST	High Speed Telemetry,		Telecommunications
	also Hubble Space		Union
	Telescope	JAXA	Japan Aerospace
IC	Integrated circuit		Exploration Agency
ICBM	Inter-Continental Ballistic	JGM	Joint Gravity Model
ICDIVI	mici Continental Bamstic	JUM	John Gravity Model
ICDM	Missile Missile	JHUAPL	Johns Hopkins University
ICU			•
	Missile		Johns Hopkins University
	Missile Instrument Control Unit,		Johns Hopkins University Applied Physics
	Missile Instrument Control Unit, also Intelligent Control	JHUAPL	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna
ICU	Missile Instrument Control Unit, also Intelligent Control Unit	JHUAPL JPL	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory
ICU	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design	JHUAPL JPL KSA	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna
ICU IDE	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment	JHUAPL JPL KSA KSC	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center
ICU IDE	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model	JHUAPL JPL KSA KSC LAM	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure
ICU IDE IDHT	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency	JHUAPL JPL KSA KSC LAM LBR	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility
ICU IDE IDHT IDM	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view	JHUAPL JPL KSA KSC LAM LBR	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic
ICU IDE IDHT IDM IF IFOV IFR	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility
ICU IDE IDHT IDM IF IFOV	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode
ICU IDE IDHT IDM IF IFOV IFR IFRB	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LED LEO	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit
ICU IDE IDHT IDM IF IFOV IFR IFRB	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit
ICU IDE IDHT IDM IF IFOV IFR IFRB	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LEAF LED LEO LEOP	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase
ICU IDE IDHT IDM IF IFOV IFR IFRB IM INMAR- SAT	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime Satellite Organization	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LEAF LED LEO LEOP LET	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase Linear energy transfer
ICU IDE IDHT IDM IF IFOV IFR IFRB	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime Satellite Organization International	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LEAF LED LEO LEOP LET LHP	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase Linear energy transfer Loop heat pipe
ICU IDE IDHT IDM IF IFOV IFR IFRB IM INMAR- SAT	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime Satellite Organization International Telecommunications	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LEAF LED LEO LEOP LET	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase Linear energy transfer Loop heat pipe Laser Interferometer
ICU IDE IDHT IDM IF IFOV IFR IFRB IM INMAR- SAT INTELSAT	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime Satellite Organization International Telecommunications Satellite Organization	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LED LEO LEO LEOP LET LHP LISA	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase Linear energy transfer Loop heat pipe Laser Interferometer Spaceborne Antenna
ICU IDE IDHT IDM IF IFOV IFR IFRB IM INMAR- SAT INTELSAT	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime Satellite Organization International Telecommunications Satellite Organization In Orbit Acceptance Review	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LEAF LED LEO LEOP LET LHP	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase Linear energy transfer Loop heat pipe Laser Interferometer Spaceborne Antenna Line impedance stabilization
ICU IDE IDHT IDM IF IFOV IFR IFRB IM INMAR- SAT INTELSAT	Missile Instrument Control Unit, also Intelligent Control Unit Integrated Design Environment Instrument data-handling and transmission Integrated Design Model Intermediate frequency Instantaneous field of view Inertial frame of reference International Frequency Registration Board Intermodulation International Maritime Satellite Organization International Telecommunications Satellite Organization	JHUAPL JPL KSA KSC LAM LBR LDEF LEAF LED LEO LEO LEOP LET LHP LISA	Johns Hopkins University Applied Physics Laboratory Jet Propulsion Laboratory K-band Steerable Antenna Kennedy Space Center Liquid Apogee Motor Low bit-rate Long Duration Exposure Facility Large European Acoustic Facility Light emitting diode Low Earth Orbit Launch and Early Orbit Phase Linear energy transfer Loop heat pipe Laser Interferometer Spaceborne Antenna