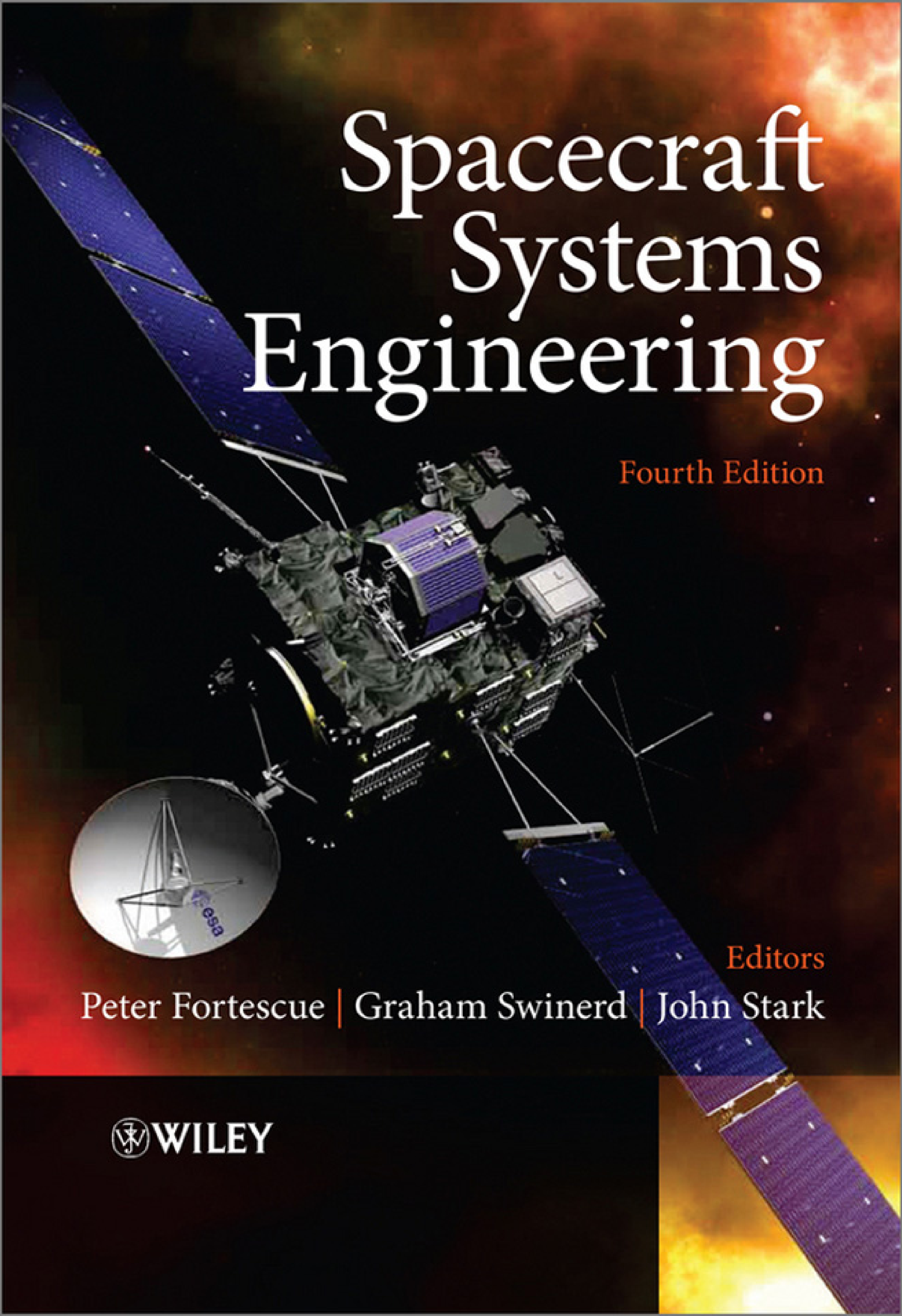

Spacecraft Systems Engineering

Fourth Edition

Editors

Peter Fortescue | Graham Swinerd | John Stark

WILEY

SPACECRAFT SYSTEMS ENGINEERING

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Dedicated to the memory of
Nicky Skinner
1978–2011

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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 L_2 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 already-extensive 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 Swinerd
Southampton, 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 (~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 Swinerd
Southampton, 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
ABM	Apogee Boost Motor
AC	Alternating current
ACS	Attitude Control System
ACU	Antenna Control Unit
A/D	Analogue to digital
ADEOS	Advanced Earth Observing System
ADR	Active Debris Removal
AFT	Abbreviated Functional Test
AGC	Automatic gain control
AIT	Assembly, integration and test
AIV	Assembly, integration and verification
AKM	Apogee Kick Motor
AM	Amplitude modulation
AMI	Active Microwave Instrument
AMOOS	Aero-Manoeuvring Orbit-to-Orbit Shuttle
AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control System
AOP	Announcement of Opportunity Package
AOS	Acquisition of signal, also Advanced Orbiting Systems
AOTV	Aero-assisted Orbital Transfer Vehicle
APM	Antenna Pointing Mechanism, also Attached Pressurized Module
APS	Active Pixel Sensor
AQAP	Allied Quality Assurance Publication
ARQ	Automatic report queuing
ASAP	Ariane Structure for Auxiliary Payloads
ASAR	Advanced Synthetic Aperture Radar
ASIC	Application-specific integrated circuit
ASK	Amplitude-shift keying
ASS	Antenna Support Structure
ASW	Address and synchronization word
ATCS	Active Thermal Control System
ATSR	Along-track Scanning Radiometer
AU	Astronomical Unit (mean distance from Earth to Sun)
BCDT	Binary code data transfer
BCH	Bose-Chaudhuri-Hocquenchem
BCR	Battery Charge Regulator
BDR	Battery Discharge Regulator
BER	Bit error rate
BMDO	Ballistic Missile Defence Organization
BMU	Battery Management Unit
BOL	Beginning of life
BPF	Band-pass filter
BPSK	Bi-phase-shift keying
BRTS	Bilateration Ranging Transponder System
BSF	Back-Surface Field
BSR	Back-Surface Reflector
CA	Contingency Analysis

CAD	Computer Aided Design
CADU	Channel Access Data Unit
CAM	Civil, Aircraft, Military
CCB	Configuration Control Board
CCD	Charge coupled device
CCIR	Comité Consultatif International de Radiocommunication
CCITT	Comité Consultatif International de Téléphonie et de Télégraphie
CCSDS	Consultative Committee for Space Data Systems
CCU	Central Communications Unit
CDF	Concurrent Design Facility
C&DH	Control and Data Handling
C&DM	Configuration and Data Management
CDMA	Code-division multiple access
CDR	Critical Design Review
CE	Concurrent Engineering
CEV	Command Execution Verification
CFDP	CCSDS File Delivery Protocol
CFRP	Carbon fibre reinforced plastic
CHAMP	CHAllenging Minisatellite Payload
CHRIS	Compact High Resolution Imaging Spectrometer
CIS	Confederation of Independent States
CLA	Coupled loads analysis
CLTU	Command Link Transfer Unit
CMG	Control moment gyroscope
CMOS	Complementary metal oxide semiconductor
CNES	Centre National d'Etudes Spatiales (French National Space Agency)
COMSAT	Communications Satellite
COTS	Commercial off the shelf
CPL	Capillary-pumped loop
CPM	Coarse pointing mechanism
CR	Corrosion resistance
CRP	Contingency Recovery Procedure
CSG	Centre Spatial Guyanais
CTM	Collapsible Tube Mast
CVCM	Collected volatile condensable materials
CW	Continuous-wave
DARPA	Defence Advanced Research Project Agency
DB	Data Base
DC	Direct current
DCP	Data Collection Platform
DoD	Department of Defence (USA)
DLR	(German Aerospace Centre)
DM	Development Model
DOF	Degree of freedom
DORIS	Determination of Orbit and Radiopositioning Integrated by Satellite
DPL	Declared Parts List
DPSK	Differential phase-shift keying
DRS	Data Relay Satellite
DSBSC	Double side-band suppressed carrier modulation
DS-CDMA	Direct Sequence Code Division Multiple Access
DSN	Deep Space Network
DSP	Digital signal processing, also Digital Signal Processor
ECR	Engineering Change Request
ECSS	European Cooperation for Space Standardization
EDA	Electrically Despun Antenna
EDAC	Error detection and correction
EEE	Electrical, Electronic and Electromechanical

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

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