Evolution of Complexity and Cost for Planetary Missions Throughout the Development Lifecycle

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Abstract— **This paper provides an update to the complexity-cost relationship presented at the Fourth IAA International Conference On Low-Cost Planetary Missions [Bearden, 2000]. [1] A significant data set exists for a thorough examination of the relationship between on-orbit performance, cost and schedule. Since 2000, the number of missions captured in the database has grown, while maintaining a stable complexity-cost relationship. This study focuses on a subset of missions with similar costs to Discovery-Class missions over the last two decades using the complexity metric to examine system development cost at various development milestones. The further from the successful mission complexity-cost trendline the study missions began their development, the greater the cost growth at launch. The magnitude of this cost growth appears to be linearly proportional to this initial "cost optimism."**

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1. INTRODUCTION

The Aerospace Corporation's Complexity Based Risk Assessment (CoBRA) methodology has linked performance attributes to overall system complexity and has related complexity, independently, to cost and schedule. CoBRA was developed in 1999 as part of a doctoral thesis [Bearden, 1999] to understand the relationship of the complexity of a system with respect to its flight system development cost, and its development schedule. [2] A database of NASA, DoD and commercial missions was investigated to develop a complexity metric as a function of series of technical and programmatic parameters. Total development cost, which includes all flight system development costs except for launch vehicle, ground systems, mission operations and data analysis, is defined in FY11 fixed year dollars.

2. DATA USED FOR STUDY

To examine the relationship among risk, cost and schedule for NASA missions, data were assembled for a majority of missions launched over the past two decades (1989 to 2011). The basis for the relationships to be discussed is a database of technical specifications, costs, development time, mass properties and operational status for the spacecraft shown in Table 1. These data fall into three general categories: (1) NASA planetary and near-Earth spacecraft; (2) NASA Earth-orbiting satellites; and (3) Other U.S. government, non-NASA satellite missions serving as a baseline for comparison.

Missions that are nearing launch or have been launched, but have yet to complete a significant portion of their science missions are included, but it is noted that success has yet to be determined. Missions that had foreign sponsorship or relied on unknown international contributions were not considered. Also, shuttle science experiments and university-developed spacecraft were not considered. No human-rated systems or launch systems were considered. All of the data collected, except for the cost information, are from public sources. The cost information is from a proprietary database maintained by The Aerospace Corporation and is therefore presented only in aggregate form without reference to specific programs.

To isolate the relationships in development lifecycle changes in complexity and cost, only a subset of NASA spacecraft missions that meet certain criteria and constraints were considered. See Table 2.

Table 1. CoBRA Mission Dataset

NASA Earth Orbiting		NASA Near-Earth/Planetary		DoD/Other Earth Orbiting	
ACRIMSat	Jason-1	ACE	Mars Odyssey	AEHF	Milstar I/II
AIM	Landsat-7	ACCESS	Mars Pathfinder	ALEXIS	MSTI 1-3
Aquarius/SAC-D	LDCM	Cassini	MAVEN	APEX	MSX
Calipso	Lewis	Clementine	MCO	DARPASAT	NFIRE
CGRO	METEOR	CONTOUR	MER	DMSP	ORBCOMM
Chandra (AXAF)	MICROLAB	Dawn	MESSENGER	DSCS	Orbital Express
CHIPSat	MMS	Deep Impact	MGS	DSP	PEGSAT
Clark	NuSTAR	DS1	MPL	FORTE	POGS/SSR
Cloudsat	OCO	Galileo	MRO	GEOEye-1	RADCAL
COBE	Polar	GENESIS	MSL	GEOLite	REX I/II
CORIOLOS	QuickSCAT	GRAIL	NEAR	GFO	SBIRS-GEO
DART	QuikTOMS	IXO	New Horizons	Globalstar	SCE
Envisat	SAMPEX	JDEM Omega	Phoenix	GLOMR I	STEP 0-4
EO-1/3	SDO	Juno	RBSP	GOES-N/R	STEX
EOS-Aqua	Seastar	JWST	SIM Lite	GPS	STPSat
EOS-Aura	SMAP	Kepler	SOHO	Ikonos	TEX
EOS-Terra	SORCE	LADEE	Spitzer (SIRTF)	Iridium	TSX-5
EUVE	SPIDR	LCROSS	ST-5	MACSAT	UFO
EXIST	SWAS	LISA	Stardust	MICROSAT	WorldView-1
FAME	Swift	LRO	STEREO	MightySat I/II	XSS-11
FAST	TDRSS	Lunar Prospector	THEIA		
FUSE	THEMIS	Magellan	TRIANA		
GALEX	TIMED	MAP	Wind		
GLAST	TOMS-EP	Mars Observer			
GPM	TOPEX/Poseiden				
GRACE	TRACE				
HESSI	TRMM				
HETE-1/2	VCL				
HST	WIRE				
IBEX	WISE				
ICESAT I/II	WXFT				
IMAGE	XTE				

Table 2. Study Missions – Subset of NASA Missions

Study Missions
Phoenix
STEREO
MESSENGER
Dawn
Genesis
NEAR
MRO
LRO
Juno

3. MEASURING COMPLEXITY

Our goal is to understand how technical and programmatic complexity relates to cost and schedule at the system level. For this reason the complexity index is derived based on performance, mass, power, destination and technology choices, to arrive at a broad representation of the system for purposes of comparison. In examining previously built systems, cost data are generally not publicly available at the subsystem level. Furthermore, low-level schedule data can also be elusive since in many cases it's not clear which element - spacecraft, subsystem, payload, launch vehicle, or some combination - is driving the development time. For these reasons a system-level assessment is desirable.

The complexity index uses a matrix of technical factors to place in rank order a new system relative to a baseline data set. Postulated complexity drivers include both general programmatic knowledge (heritage, requirements changes, foreign involvement, amount of redundancy, contractor experience, specification level, etc.) that require some measure of subjective judgment, and demonstrable objective technical parameters (mass, power, performance, pointing accuracy, downlink data rate, technology choices, etc.). In this case we have chosen to emphasize objective technical parameters. The parameters that contribute to the calculated spacecraft complexity index, statistics of interest, and an example calculation for satellite are summarized in Table 3. The total flight system development costs (payload instruments and spacecraft bus, excluding launch and operations) and development times (period of time from contract start until ready for launch) are the independent variables against which the complexity is compared.

To estimate spacecraft complexity we:

(1) Identify the parameters that drive the system design;

(2) Quantify the identified parameters;

(3) Estimate complexity for the individual parameters relative to the data set as a whole;

(4) Combine the parameters into an aggregate complexity index.

Parameters were selected based on requirements that exert a significant influence on spacecraft design or development. The relative importance of the parameters contributing to the complexity index and correlation among them in representing and/or driving technology selections remains to be fully investigated. Correlation of variables has the potential effect of weighting the estimate toward a single subsystem if an excessive number of interdependent parameters are used (e.g., solar array area is dependent on solar cell type, orbit geometry and required end-of-life power, all of which contribute to the complexity calculation) or under-representing the contribution of a particular subsystem to overall system complexity if an insufficient number of parameters are used. A balance is achieved by assuring that at least one parameter and at most six parameters are used to represent each of the traditional spacecraft subsystems.

All parameters are demonstrable parameters dictated by project, mission or system requirements. The strength of using a number of interrelated parameters is that peculiarities associated with the specific implementation approach will be averaged out. These descriptive parameters (number of instruments, mass, technical performance, subsystem characteristics, technological choices, etc.) are normalized based on the applicable range as designated by the programs in the database. There are two types of calculations:

(1) Discrete choices such as propulsion type (none, cold gas, monopropellant, bipropellant, or ion engine);

Discrete choices are determined as follows:

$$f_i = (i - 1)/(m-1) \quad (1)$$

$i = 1 \ldots m$, where m is the number of discrete choices

(2) Continuous parameters (e.g . mass, power, pointing accuracy) that represent a range of potential values bounded by a minimum and maximum.

Continuous (non-discrete) parameters are analyzed using the Microsoft Excel® function PERCENTRANK that returns the rank of a value in a data set as a percentage of the data set. This function is used to evaluate the relative standing of a value within the data set. For example, PERCENTRANK can be used to evaluate the standing of launch mass among all launch masses in the database. If the value does not match one of the values in the array, PERCENTRANK interpolates to return the correct percentage rank. The syntax is as follows:

$$f_j = \text{PERCENTRANK}(Array, X) \; j = 1 \ldots n \quad (2)$$

where, *Array* is the range of data with numeric values that defines relative standing[1], *X* is the value for which we want to know the rank, and n is the number of continuous parameters.

With f_i and f_j representing discrete and continuous complexity parameters, the overall complexity factor, Fc, is defined as:

$$F_c = (\Sigma f_i + \Sigma f_j)/(m+n) \; \mathrm{i} = 1 \ldots m, \mathrm{j} = 1 \ldots n \quad (3)$$

[1] Note that for parameters where a smaller number implies a more strenuous requirement such as pointing accuracy and knowledge that f_j is calculated as 1-PERCENTRANK(Array, X).

Table 3. Factors Contributing to Complexity Index Calculation

Complexity-based Risk Analysis (CoBRA)

Factor	Unit	Min	Median	Mean	Max	Example Satellite	
Development Cost (Project)	(FY11$M)	2.2	230	490	4463	857	
Development Time (Project)	(mos)	12	48	53	126	62	
Payload Mass	(kg)	0	120	317	6065	160	63%
Payload Average Power	(W)	0	107	387	6000	175	67%
Payload Peak Power	(W)	0	199	569	13025	175	46%
Payload Data Rate (average)	(kbps)	0	196	29871	330000	10	18%
Number of Payloads		1	3	4	27	10	93%
Payload Type		0	2	2	4	1	12%
Data Volume	(MB/day)	0	458	510675	21168000	107	32%
Foreign Partnership		{ None, GS, LV, SC Bus, PL, mult PL }				0	0%
Design Life	(mos)	0	36	52	330	30	42%
Launch Mass (Wet)	(kg)	17	658	1339	18189	371	30%
Satellite Mass (Dry)	(kg)	17	594	1102	16329	325	30%
Bus Dry Mass	(kg)	15	421	724	10264	165	21%
Level of Redundancy	(%)	0%	20%	40%	100%	0%	0%
Orbit Regime		{ STS/ISS, GEO, LEO/MEO, H-LEO/Dip, NE, Interplan (au) }				2.0	76%
BOL Power	(W)	12	688	1663	18000	296	24%
Orbit Average Power	(W)	3	327	732	6687	260	39%
EOL Power	(W)	3	577	1301	11264	271	29%
Solar Array Area	(m^2)	0	6	14	175	1.0	8%
Solar Cell Type		{ None/Si, GaAs, GaAs-mult, GaAs-conc, RTG/R }				GaAs	50%
Battery Type		{ Lead-acid, NiCd, SNiCd, NiH2, Li-Ion }				li-ion	100%
Battery Capacity	(A-hr)	1	37	61	1222		
# Articulated Structures		0	0	1	13	0	0%
# Deployed Structures		0	1	2	20	0	0%
Solar Array Configuration		{ body-fixed, deployed, single-axis, articulated }				D	33%
Structures Material		{ Aluminum, Al w/Comp-face, Exotic, Composite }				Al	0%
ADCS Type		{ None/Magnetic, GG, Spin, 3-axis, Hi-spin, 3-axis (ST), Dual }				Spin	40%
Pointing Accuracy	(deg)	1.70E-06	0.1000	1.0782	20	1.00000	22%
Pointing Knowledge	(deg)	1.11E-06	0.0250	0.6459	20	0.01000	68%
#Thrusters+Tanks	(#)	0	9	10	52	11	60%
Propulsion Type		{ None, Cold-Gas, Mono, Biprop-(blow,pres), OB+US, Ion }				Mono	40%
Total Impulse (delta-V)	(m/sec)	0	117	1203	80130	320	70%
Downlink Comm Band		{ UHF/VHF/SHF, S, L, X, Ka/Ku, EHF, Opt }				S	20%
Max Downlink Data Rate	(kbps)	1	1280	37587	1460926	78	20%
Max Uplink Command Data Rate	(kbps)	0	2	276	40000	1.0	8%
Data Storage Capacity	(Mbytes)	0	580	36704	3000000	1024	57%
Thermal Type		{ passive, heaters, active, cryo }				heaters	33%
Multi-Element System?		{ single-sc, tdrs, mult (cl, aerobr, rend), entry/landed }				Single	0%
Complexity Index		2%	47%	45%	78%		35%
Normalized Complexity Index		0%	59%	56%	100%		43%

The mean complexity index is determined by averaging the individual factors. Equal weighting is used so that the analysis does not differentiate among parameters or allow any particular parameter to dominate. Fc is then normalized relative to the maximum and minimum to arrive at a percentage between 0 and 100%.

4. EXAMINATION OF TRENDS

Using the process described above, a complexity index was calculated for the programs in Table 1, using the parameters shown in Table 3. The updated plot, Figure 1, displays a plot of complexity, as calculated by the CoBRA process, relative to the cost of satellite systems that were successful, impaired, suffered a failure, or status is yet-to-be determined. There are several conclusions that can be drawn from this figure. First, a high correlation between complexity and cost is apparent. Second, the average complexity of impaired and failed missions is higher than that of successful missions for the same cost. While the complexity index does not predict the manner in which a failure will occur, it does define a framework within which a new mission being considered may be compared with past missions. Bitten, Bearden and Emmons [2005] took the CoBRA methodology a step further with multi-variable regression analysis performed for a set of NASA science missions to determine quantitative relationships between complexity as a function of cost and schedule, schedule as a function of cost and complexity, and cost as a function of schedule and complexity. [3]

Figure 2 is an example of the typical complexity and cost growth of missions during their developmental lifecycle, with initial "cost optimism."

Also captured is the development cost estimates (phases B-D) at milestones CSR, PDR, CDR, and launch. The changes in cost growth between CSR and launch as a function of distance from the overall successful mission trendline is shown in Figure 3.

Several observations can be drawn from this data. First, as projects progress in their development lifecycle, costs increase for all missions except NEAR, which had a large cost reduction early in development. Also, this relationship appears to be linearly proportional to the extent of initial cost estimation optimism at CSR. If this relationship holds over time and for a large data set, it could be of tremendous utility in assessing new mission concepts' potential for cost growth.

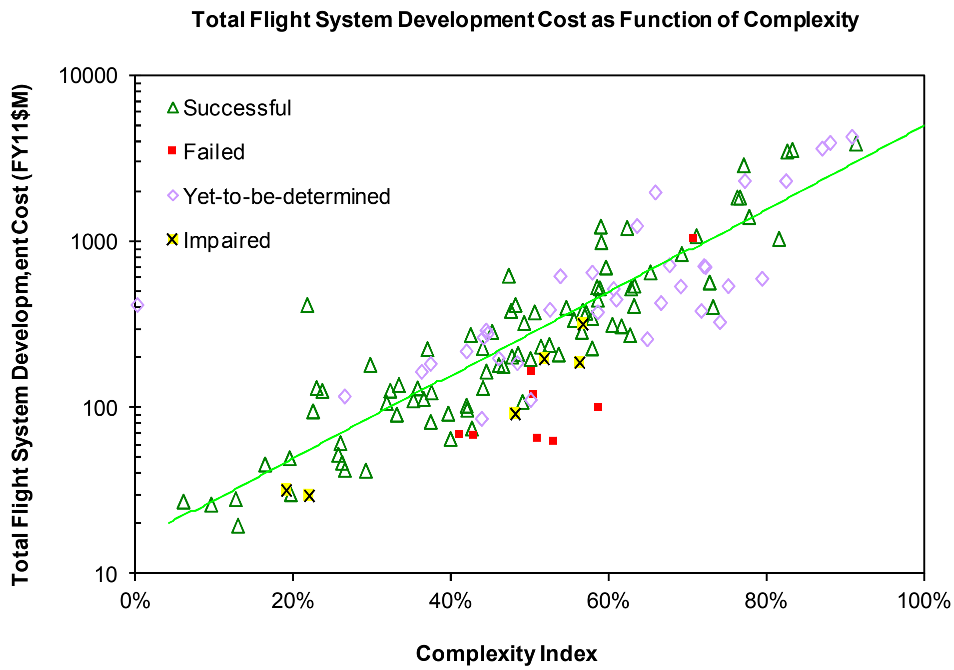

Figure 1. Updated Complexity and Cost Relationship

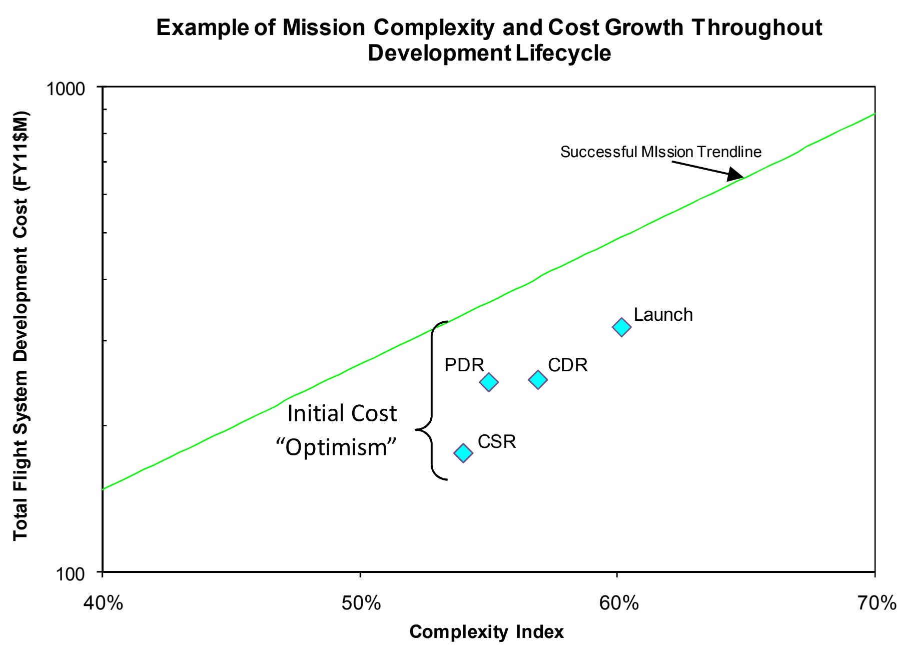

Figure 2. Complexity and Cost Growth throughout Development Lifecycle

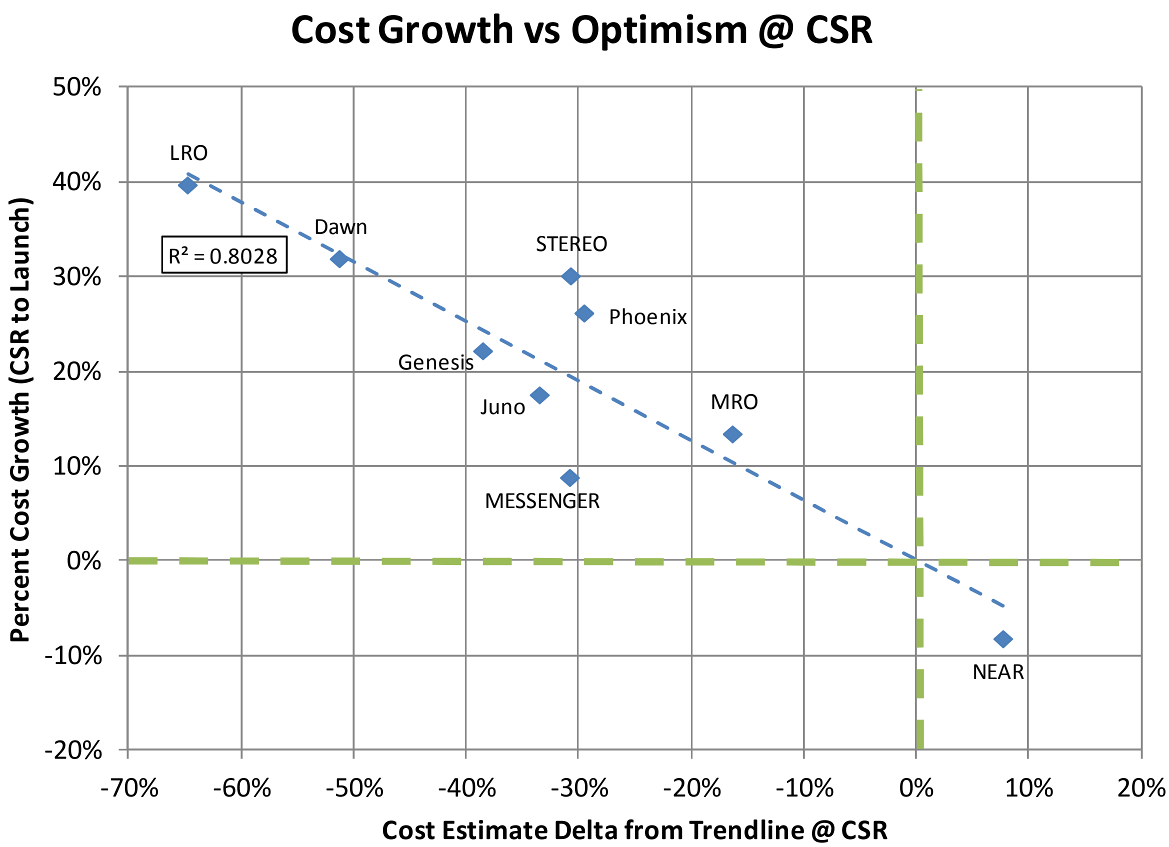

Figure 3. Cost Growth as a Function of Early Milestone Optimism

5. Summary

As the CoBRA database mission-set has increased over the last decade, the strong complexity-cost relationship has continued. For the study mission subset selected, the relationship between early lifecycle cost optimism and development lifecycle cost growth appear to follow a linear trend. This relationship demands further study. As new missions are added to the larger dataset, more of the intermediate milestone date is becoming available. Intermediate milestone data is being made available via retrospective studies such as NASA's Cost Analysis Data Requirement (CADRe). Similar follow-on studies of larger datasets are needed to strengthen this development lifecycle cost growth relationship.

6. References

[1] Bearden, David A., A Complexity-Based Risk Assessment Of Low-Cost Planetary Missions: When Is A Mission Too Fast And Too Cheap?, Fourth IAA International Conference On Low-Cost Planetary Missions, May 2-5, 2000.

[2] Bearden, D.A.: A Methodology for Technology Insertion Assessment Balancing Performance, Cost and Risk, Ph.D. Dissertation, University of Southern California, May, 1999.

[3] Bitten, R.E., Bearden, D.A. and Emmons, D.E.: "A Quantitative Assessment Of Complexity, Cost, And Schedule: Achieving a Balanced Approach For Program Success", Sixth IAA International Conference On Low-Cost Planetary Missions, May 2005.

Biographies

David Bearden serves as General Manager of the NASA Programs Division within the Civil and Commercial Operations at Aerospace, and is responsible for management and technical leadership of the company's support to NASA. He leads a multi-disciplinary team of scientists and engineers that develops and sustains technical consulting business from civil agencies, commercial companies, and international space clients. David has over 20 years of technical and management experience in the acquisition and development of advanced technology space systems and holds a Ph.D. in Aerospace Engineering from the University of Southern California.

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ACRONYMS

ACE Advanced Composition Experiment
ACRIMSat Active Cavity Radiometer Irradiance Monitor Satellite
AEHF Advanced Extremely High Frequency
AIM Aeronomy of Ice in the Mesosphere
Al Aluminum
ALEXIS Array of Low-Energy X-ray Imaging Spectrometers
APEX Advanced Photovoltaic and Electronics Experiment
APL Applied Physics Laboratory
Aquarius/SAC-D Satelite de Aplicaciones Cientificas-D
ATP authority to proceed
au astronomical units
A-hr Ampere hours
BATC Ball Aerospace Technology Corporation
Biprop bipropellant
BMDO Ballistic Missile Defense Organization
BOL Beginning of Life
CGRO Compton Gamma Ray Observatory
Chandra (AXAF) Advanced X-ray Astrophysics Facility
CHIPSat Cosmic Hot Interstellar Plasma Spectrometer
CNES French space agency
COBE Cosmic Background Explorer
CONAE Argentine Space Commission
CONTOUR Comet Nucleus Tour
CTA Computer Technology Associates
DARPA Defense Advanced Research Project Administration
DART Demonstration for Autonomous Rendezvous Technology
deg degrees
DMSP Defense Meteorological Satellite Program
DOD Department of Defense
DOE Department of Energy
DSI Defense Systems, Inc.
DS-1 Deep Space 1 Mission
DSCS Defense Satellite Communications System
DSP Defense Support Program
EO-1 Earth Observing 1 Mission
EOL End of Life
EOS Earth Observing System
ESSP Earth System Science Pathfinder
EUVE Extreme Ultra-Violet Explorer
EXIST Energetic X-ray Imaging Survey Telescope
FAME Full-sky Astrometric Mapping Explorer
FAST Fast Auroral Snapshot Explorer
FUSE Far Ultraviolet Spectroscopic Explorer
FORTE Fast On-orbit Recording of Transient Events
FY fiscal year
GaAs gallium arsenide
GALEX GALaxy Explorer
GEO Geosynchronous Earth Orbit
GFO Geosat Follow-on
GLAST Gamma-ray Space Telescope

GLOMR Global Low Orbiting Message Relay
GOES Geostationary Operational Environmental Satellite
GPM Global Precipitation Measurement
GPS Global Positioning System
GRACE Gravity Recovery and Climate Experiment
GRAIL Gravity Recovery and Interior Laboratory
GSFC Goddard Space Flight Center
HESSI High Energy Solar Spectroscopic Imager
HETE High Energy Transient Experiment
HST Hubble Space Telescope
IBEX Interstellar Boundary Explorer
ICESAT Ice, Cloud,and land Elevation Satellite
IMAGE Imager for Magnetopause-to-Aurora Global Exploration
IXO International X-ray Observator
JDEM Joint Dark Energy Mission
JHU Johns Hopkins University
JPL Jet Propulsion Laboratory
JWST James Webb Space Telescope
kbps kilobits per second
kg kilogram
KSLOC thousand software lines of code
LADEE Lunar Atmosphere and Dust Experiment Explorer
LANL Los Alamos National Laboratory
LaRC Langley Research Center
LASP Laboratory for Atmospheric and Space Physics
LCROSS Lunar Crater Observation and Sensing Satellite
LDCM Landsat Data Continuity Mission
LEO low Earth orbit
Lib Libration Point
Li-ion Lithium-ion
LISA Laser Interferometer Space Antenna
LLC Limited Liability Corporation
LMA Lockheed Martin Astronautics
LRO Lunar Reconnaissance Orbiter
LV Launch Vehicle
MACSAT Multiple-Access Communications Satellite
MAP Microwave Anisotropy Probe
MAVEN Mars Atmosphere and Volatile Evolution Mission
Mbytes megabytes
MCO Mars Climate Orbiter
MEO Medium Earth Orbit
MER Mars Explorer Rover
MESSENGER MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MGS Meteosat Second Generation
MIT Massachusetts Institute of Technology
MGS Mars Global Surveyor
MIDEX Medium-Class Explorers
MIPS Milliens Instructions Per Second
MIT Massachusetts Institute of Technology
m meter
MMS Magnetospheric Multiscale
MPL Mars Polar Lander

MRO Mars Reconnaissance Orbiter
MSFC Marshall Space Flight Center
MSL Mars Science Lander
MSTI Miniature Sensor Technology Integration
MSX Midcourse Space Experiment
NASA National Aeronautics and Space Administration
NEAR Near-Earth Asteroid Rendezvous Mission
NFIRE Near Field Infrared Experiment
NiCd Nickel Cadmium
NiH_2 Nickel Hydrogen
NOAA National Oceanic and Atmospheric Agency
NRL Naval Research Laboratory
NRO National Reconnaissance Office
NuSTAR Nuclear Spectroscopic Telescope Array
OCO Orbiting Carbon Observatory
ONR Office of Naval Research
PEGSAT Pegasus Satellite
POGS/SSR Polar-Orbit Geomagnetic Survey Solid-State Recorder
PL payload
QuickSCAT Quick Scatterometer
QuikTOMS Quick Total Ozone Mapping Spectrometer
R Correlation Coefficient
RADCAL radiation calibration
RBSP Radiation Belt Storm Probes
REX Radiation Experiment
SAC-B Satelite de Aplicaciones Cientificas B mission
SAMPEX Solar Anomalous and Magnetospheric Particle Explorer
SBIRS Space Based Infrared System
SC Spacecraft
SCE Selective Communications Experiment
SDIO Strategic Defense Initiative Organization
SDO Solar Dynamics Observatory
sec second
SHF Super High Frequency
SIM Space Interferometry Mission
SIRTF Space InfraRed Telescope Facility
SMAP Soil Moisture Active Passive
SMEX Small Explorer Program
SNiCd Super Nickel Cadmium
SNL Sandia National Laboratory
SOHO Solar & Heliospheric Observatory
SORCE Solar Radiation and Climate Experiment
SPIDR Spectroscopy and Photometry of the IGMs Diffuse Radiation
SSTI Small Spacecraft Technology Initiative
ST Star Tracker
ST Space Technology
STEP Space Test Experiment Platform
STEREO Solar TERestrial Observatory
STEX Space Technology Experiment
STP Space Test Program
SWAS Submillimeter Wave Astronomy Satellite

TDRSS Tracking and Data Relay Satellite System
TEX Transceiver Experiment
THEMIS Time History of Events and Macroscale Interactions during Substorms
TIMED Thermosphere Ionosphere Mesosphere Energetics and Dynamics
TOMS-EP Total Ozone Mapping Spectrometer - Earth Probe
TOPEX Topography Experiment
TRACE Transition Region and Coronal Explorer
TRMM Tropical Rainfall Measuring Mission
TSX Tri-Service Experiment
UFO UHF Follow-On
UHF Ultra-High Frequency
VCL Vegetative Canopy Lidar
VHF Very-High Frequency
W Watt
WIRE Wide-field Infrared Experiment
WISE Wide-Field Infrared Survey Explorer
WXFT Wide Field X-Ray Telescope Mission
XSS eXperimental Satellite System
XTE X-ray Timing Explorer