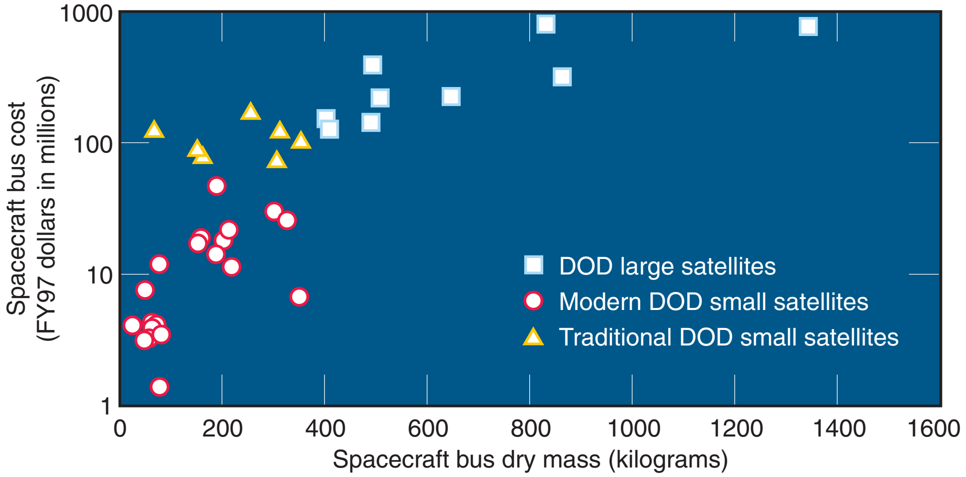
Small-Satellite Costs

David A. Bearden

Highly capable small satellites are commonplace today, but this wasn't always the case. It wasn't until the late 1980s that modern small satellites came on the scene. This new breed of low-profile, low-cost space system was built by maximizing the use of existing components and off-the-shelf technology and minimizing developmental efforts. At the time, many thought that because of their functional and operational characteristics and their low acquisition costs, these small systems would become more prevalent than the larger systems built during the previous 30 years.

But exactly which spacecraft fell into the new category? A precise description of small satellites, or "lightsats," as they were also called, was lacking in the space literature of the day. The terms meant different things to different people. Some established a mass threshold (e.g., 500 kilograms) to indicate when a satellite was small; others used cost as a criterion; still others used size. Even scarcer than good descriptions of small satellites, however, were guidelines for cost estimation of small-satellite projects. Clearly, a more useful definition of small space systems was needed.

By the 1990s, because of increased interest in small satellites for military, commercial, and academic research applications, the Air Force Space and Missile Systems Center (SMC) and the National Reconnaissance Office (NRO) asked The Aerospace Corporation for information about



Dollars-per-kilogram comparison of DOD large satellites (500 dollars per kilogram), modern small satellites (100 dollars per kilogram), and traditional small satellites (150 dollars per kilogram). Data points for these three categories cluster differently, and regression analysis shows that each set of points determines a different cost-estimating relationship. This information confirms the need for a new model using contemporary small satellites as its basis.

capabilities and costs of such systems. In response, Aerospace commissioned a study to compare cost and performance characteristics of small satellites with those of larger, traditional systems. Of specific interest was the ability to examine tradeoffs between cost and risk to allow assessment of how traditional risk-management philosophies might be affected by the adoption of small-satellite designs.

Estimating costs for small systems raised many questions. What parameters drove the cost of small satellites? Were traditional parameters known to drive the cost of large systems still applicable? How did small systems compare with large ones? Did small-satellite acquisition philosophies, which prompted reductions in levels of oversight, independent reviews, and paperwork, enable a reduction in cost-per-unit capability? What advantages might small satellites offer for rapid incorporation of new technologies? Could they help reduce the long development cycle for military space programs? Were small satellites really economical for operational applications, such as navigation and communication?

These questions led to a series of studies on technical and economic issues involved in designing, manufacturing, and operating small satellites. The studies found that existing spacecraft cost models, developed during the previous 30 years to support the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD), were of limited utility because of fundamental differences in technical characteristics and acquisition and development philosophies between small-satellite and traditional-satellite programs.

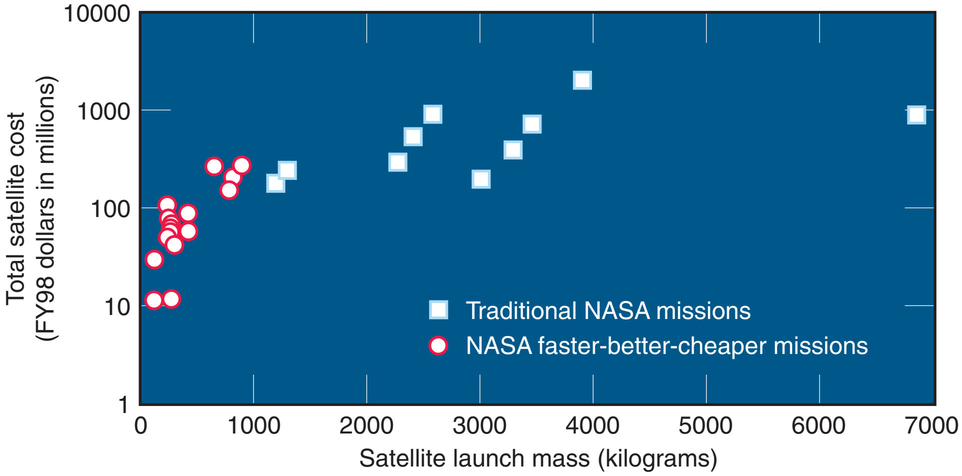
This finding prompted NASA and DOD to seek cost-analysis methods and models specifically tailored to small-satellite programs. To meet this need, Aerospace eventually developed the Small Satellite Cost Model, a small-satellite trade-study software tool that captures cost, performance, and risk information within a single framework. Before looking at the development of Aerospace's trade-study tool, though, it will be valuable to backtrack to the late 1980s and review just exactly how small-spacecraft programs had been perceived.

Streamlined Development Activities

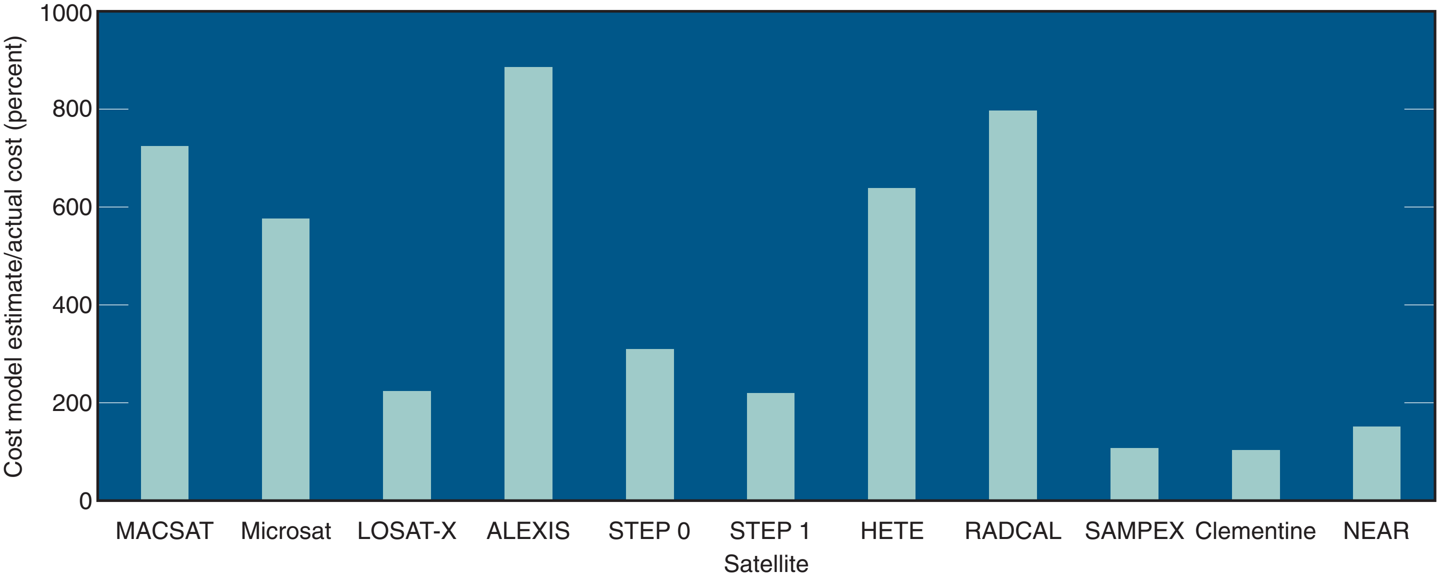
In the 1980s, the DOD Advanced Research Projects Agency and the United States Air Force Space Test Program served as the primary sources of funding for small satellites, which typically were used for technology experiments. The Space Test Program coordinated experimental payload flights for the Army, Navy, Air Force, and other government agencies. Reduced development complexity and required launch-vehicle size enabled affordable, frequent access to space for research applications. Relatively low acquisition costs and short development schedules also allowed university laboratories to participate, providing individual researchers access to space—a privilege previously reserved only for well-funded government organizations.

Small satellites were procured under a specifically defined "low cost" philosophy. They were smaller in size and were built with maximum use of existing hardware. A smaller business base (i.e., a reduced number of participating contractors) was involved in the development process, and it was perceived that small satellites represented a niche market relative to the more prevalent large systems. Mission timelines from approval to launch were on the order of 24 to 48 months, with an on-orbit life of 6 to 18 months. Launch costs, either for an existing dedicated small launcher or for a secondary payload on a large launcher, remained high, but developments such as the Pegasus air-launched vehicle and new small launchers (such as Taurus and Athena) offered promise of lowering these costs. Additionally, small-satellite flight and ground systems typically used the most mature hardware and software available to minimize technology-development and flight-certification costs.

Emerging advances in microelectronics, software, and lightweight components enabled system-level downsizing. Spacecraft often cost more than $200 thousand per



This graph compares the dollars-per-kilogram ratio for traditional NASA missions (900 dollars per kilogram) with the ratio as noted in NASA's faster-better-cheaper missions (120 dollars per kilogram). It's clear that the different sets of data points determine markedly different cost-estimating regimes.



A cost-percentage comparison that makes use of an older model and the updated dollars-per-kilogram relationships shown in previous graphs to estimate modern small-satellite costs. Each bar's height represents the percentage difference between a satellite's estimated cost and its actual cost. Thus for Clementine, with a percentage of 109%, the older model's estimate was twice the actual cost, and for RADCAL, with a percentage of 801%, the older model's estimated cost was nine times the actual cost. Because the estimates far outweighed the real cost in many cases, the chart illustrates the inadequacy of a traditional cost model for modern small satellites.

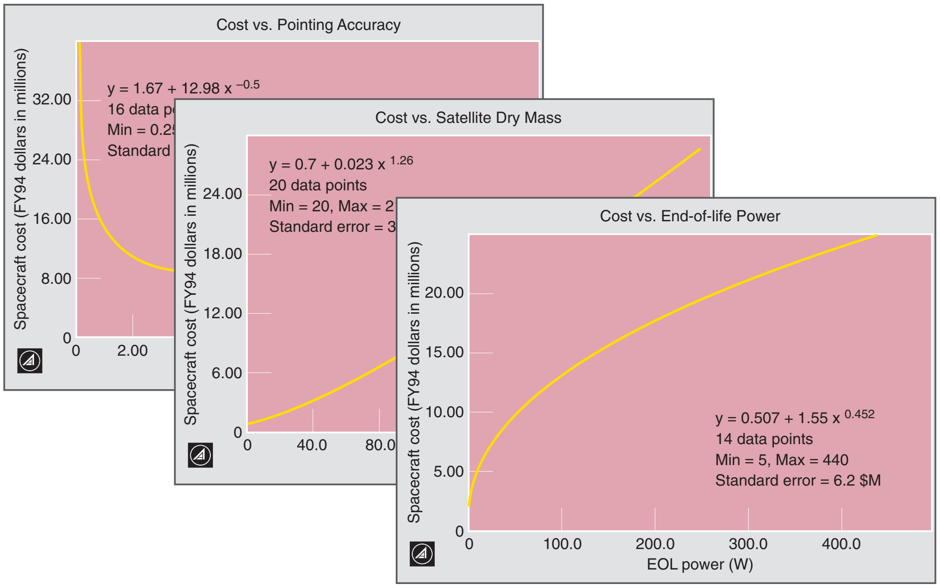
kilogram and could reach $1 million per kilogram with delivery-to-space costs included. With miniaturization, every kilogram saved in the spacecraft bus or instruments represented a possible saving of up to five kilograms in launch, onboard propulsion, and attitude-control systems mass. Reduced power demands from microelectronics, instruments, and sensors could produce similar payoffs. For interplanetary missions, reduced mass had the capability to produce indirect cost savings through shorter transit times and mission duration. All this downsizing eliminated the need for large facilities and costly equipment such as high bays, clean-room areas, test facilities, and special handling equipment and containers.

Engineering development units—prototypes built before the actual construction of flight hardware—were not built; instead a protoflight approach was favored, where a single unit served as both the engineering model and the actual flight item. Quality parts were used where possible, but strict adherence to rigid military specifications was avoided. Redundancy—the use of multiple components for backup in the event the primary component fails—was also avoided in favor of simpler designs. Designers relied on multifunctional subsystems and software to allow operational work-arounds or alternate performance modes that could provide functionality if something went wrong during a mission.

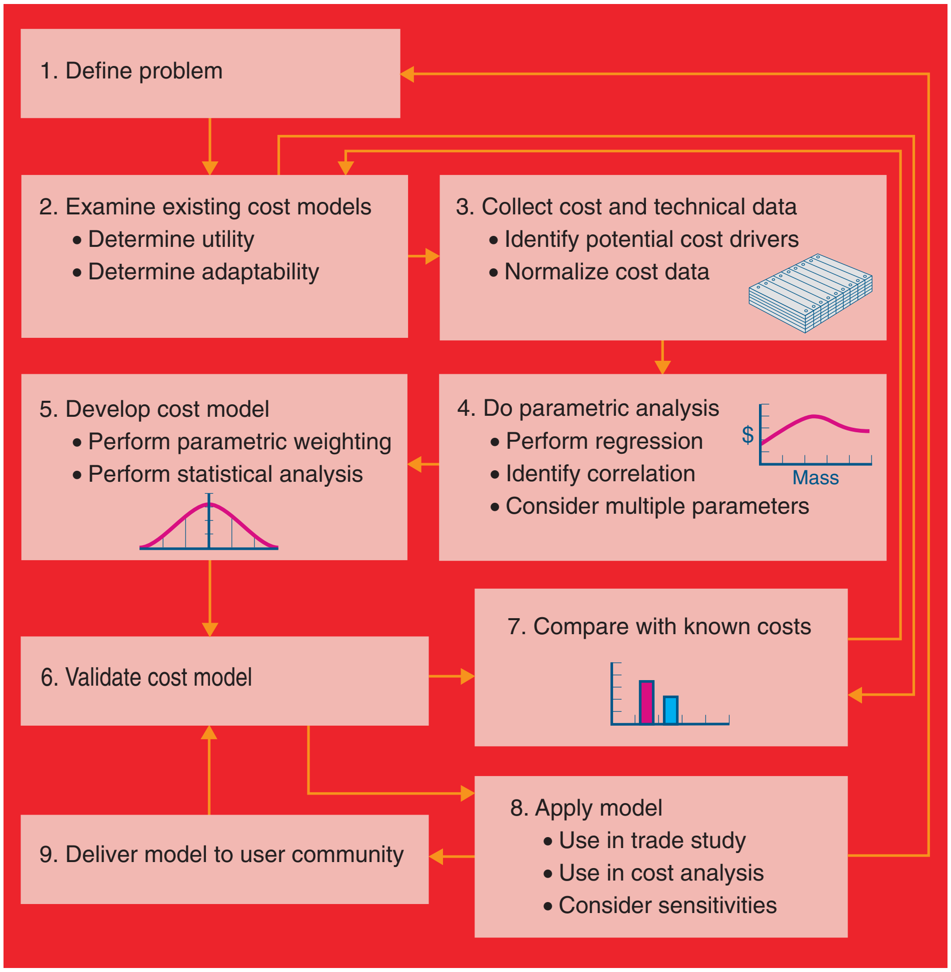
As a result of these unorthodox approaches that sought ways to save time and money, small-spacecraft programs came to be perceived as fast-paced, streamlined development activities. Dedicated project leaders with small teams were given full technical and budgetary responsibility with goals tailored around what could be done inexpensively on a short schedule. Fixed-price contracts became the norm, and requirement changes (and associated budgetary adjustments) were held to a minimum.

The Next Decade

With the advent of the 1990s came a movement toward realizing routine access to space. The development of a broad array of expendable launch vehicles provided increased access to orbit for many different kinds of payloads. Satellite programs attempted to incorporate advanced technology and demonstrate that fast development cycles, low acquisition costs, and small flexible project teams could produce highly useful smaller spacecraft. This different paradigm opened up new classes of space applications, notably in Earth science, commercial mobile-communications, and remote-sensing arenas.



System-level cost-estimating relationships that were developed for early versions of the Small Satellite Cost Model. The first cost-estimating relationships related total spacecraft bus cost to individual parameters such as mass, power, or pointing accuracy. These were the early predecessors of today's more sophisticated cost model that represents costs at the subsystem level utilizing a variety of cost drivers.



The cost modeling process. This is an ongoing iterative process that involves collecting data and performing regression analysis to arrive at cost-estimating relationships. The data are validated against actual program costs. The model is delivered to the users for trade analyses.

Small-spacecraft designers, in their quest to reduce costs through use of off-the-shelf technology, in many cases pioneered the use of microcircuitry and other miniaturized devices in space. Whereas small satellites had been unstabilized, battery-powered, single-frequency, store-and-forward spacecraft with limited applicability to operational space endeavors, the level of functionality achievable in small spacecraft took a dramatic leap forward in the early 1990s, mainly because of the availability of increased space-compatible computational power and memory. These advances led to the current rich suite of spacecraft bus capabilities and the large array of missions using small spacecraft.

The trend toward cost reduction and streamlined management continued to gain momentum with increased interest in small spacecraft from NASA and DOD. A shift in philosophy, where a greater tolerance for risk was assumed, was evident in programs like the NASA-sponsored Small and Medium Explorer Programs, the Ballistic Missile Defense Organization-sponsored Clementine, DOD-sponsored Space Test Experiment Platforms, and the Small Satellite Technology Initiative's Lewis and Clark, among others. The end of the Cold War (in 1991) and the drive toward reduced development and launch costs created a political and budgetary imperative where small satellites were viewed as one of the few vehicles available for science and technology missions.

In response to budget pressures and in the wake of several highly publicized lost or impaired billion-dollar missions, NASA's administrator Dan Goldin in 1992 embraced small spacecraft and promoted the notion of a "faster-better-cheaper" approach for many of NASA's missions. The programs implemented as a result of this tactic dictated faster and cheaper by specifying launch year and imposing a firm funding cap. These constraints laid the groundwork for what would become a decade of ongoing controversy about the definition and success of faster-better-cheaper.

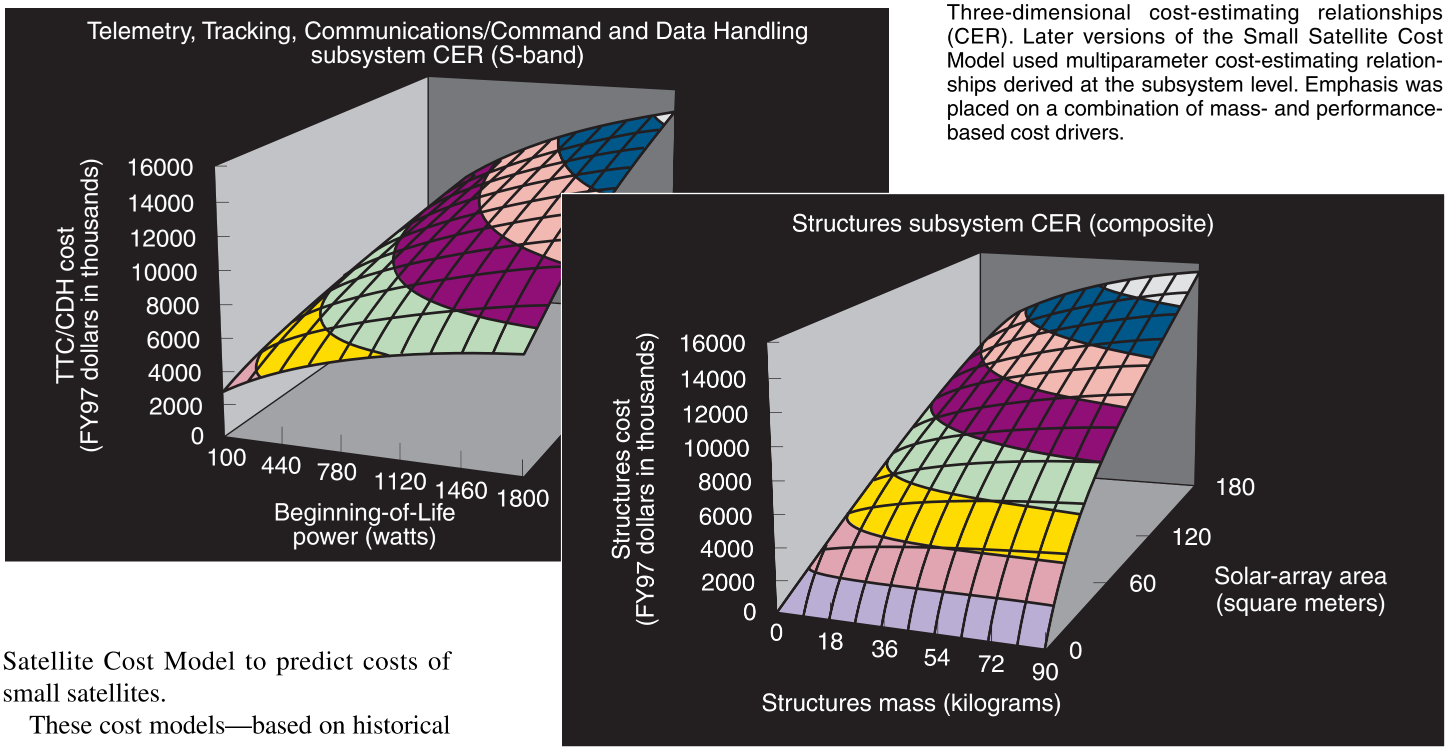
The Need for a New Model

It was against this backdrop that Aerospace began collecting a large body of information concerning technologies and program-management techniques that affected small-satellite cost-effectiveness. The programmatic aspects of traditional satellite programs (e.g., long schedules, large amounts of documentation, rigorous procedures, and risk abatement) were known to dramatically affect cost. In particular, two distinct but interrelated factors drove the cost of the system: what was built and how it was procured. In many cases, how the system was procured appeared to be as important as what was procured because cost and schedule were dependent on the acquisition environment.

A study that compared spacecraft mass versus cost for traditional small spacecraft of the 1960s and 1970s, traditional large spacecraft of the 1970s and 1980s, and modern (post-1990) small spacecraft revealed two important messages. First, the modern small spacecraft differed dramatically from traditional large spacecraft as well as their similarly sized cousins of the past. It was postulated that the latter difference, as evidenced by cost reduction, was the result of a combination of new business approaches and advanced technology. Second, cost and spacecraft sizing models based on systems or technologies for traditional spacecraft were inappropriate for assessing modern small satellites.

This was an understandable departure from traditional-spacecraft cost trends. New developments in technology are often based on empirical models that characterize historical trends, with the assumption that future missions will to some degree reflect these trends. However, in cases where major technology advancements are realized or where fundamental paradigms shift, assumptions based on traditional approaches may not apply. It became clear that estimating small-system costs was one such case.

Early small-satellite studies showed that cost-reduction measures applied to small-satellite programs resulted in system costs substantially lower than those estimated by traditional (primarily mass-based) parametric cost-estimating relationships (equations that predict cost as a function of one or more drivers). The studies analyzed the applicability of available cost models such as the Air Force Unmanned Spacecraft Cost Model and the Aerospace



Three-dimensional cost-estimating relationships (CER). Later versions of the Small Satellite Cost Model used multiparameter cost-estimating relationships derived at the subsystem level. Emphasis was placed on a combination of mass- and performance-based cost drivers.

Satellite Cost Model to predict costs of small satellites.

These cost models—based on historical costs and technical parameters of traditional large satellites developed primarily for military space programs—were found inappropriate for cost analyses of small-satellite programs. It became readily apparent in comparing actual costs against costs estimated by these models that a new model, dedicated to this new class of mission, was needed. Credible parametric cost estimates for small-satellite systems required new cost-estimating relationships derived from a cost and technical database of modern small satellites.

The Making of a Model

Developing a small-satellite cost model that related technical parameters and physical characteristics to cost soon became the primary objective of small-satellite studies. To accomplish this, a broad study of small satellites was performed, with emphasis on the following tasks:

- definition of small satellite and identification of small-satellite programs
- collection of small-satellite cost and technical data from the Air Force, NASA, and university, government laboratory, and industry sources
- examination of cost-reduction techniques used by small-satellite contractors and sponsors
- performance of parametric analysis to determine which factors should be used in the derivation of cost-estimating relationships by using best-fit regressions on data where cost correlation is evident
- development and validation of a cost model with parametrics and statistics; evaluation of the cost model by performance of cost and cost-sensitivity analyses on small-satellite systems under development
- creation of a corporate knowledge base of ongoing small-satellite activities and capabilities, technology-insertion opportunities, and project histories for lessons learned, systems studies, etc.
- maintenance of a corporate presence in the small-satellite community to advise customers about relevant developments
- development of a cadre of people with expertise and tools for continued studies of the applicability of small satellites to military, civil, and commercial missions

The cost-modeling process entailed aggressive data acquisition through collaboration with organizations responsible for developing small satellites. One unanticipated challenge was actually gaining access to cost data. Small-satellite contractors, in their quest to reduce costs, would often not be contractually bound to deliver detailed cost data, so in many cases costs were not available. Despite this difficulty, Aerospace collected data over a period of two to three years for about 20 small-satellite programs at the system level (i.e., total spacecraft or spacecraft bus costs only). From this initial database, analysts derived parametric costing relationships as a function of performance measures and physical characteristics. The model estimated protoflight development costs and cost sensitivities to individual parameters at the system level.

The model was of great value in instances where evaluations needed to be performed on varying proposals with differing degrees of detail or when limited information was available, as is often the case in an early concept-development phase.

The Second-Generation Cost Model

While initial system-level small-satellite studies were sponsored by DOD and internal Aerospace research and development, in 1995, the need to respond to increasingly frequent questions about NASA-sponsored small-satellite architectures and a need for refined small-satellite system analysis at the subsystem level prompted NASA to seek better cost-analysis methods and models specifically tailored to small-satellite programs. Consequently, NASA asked Aerospace to gather information regarding capabilities and costs of small satellites and to develop a set of subsystem-level small-satellite cost-estimating relationships.

To allow assessment of a complete spacecraft bus cost, Aerospace collected more data in order to be able to derive cost-estimating relationships for each of the spacecraft bus subsystems:

Small-Satellite Database

NASA Small Planetary Satellites

Program	Sponsor	Spacecraft Contractor	Launch Mass (kilograms)	Launch Date	Launch Vehicle	Mission
Clementine	BMDO/NASA	NRL	494	Jan 94	Titan II	Lunar mapping
NEAR	NASA	JHU/APL	805	Feb 96	Delta II	Asteroid mapping
MGS	NASA	Lockheed Martin	651	Nov 96	Delta II	Mars mapping
Mars Pathfinder	NASA	JPL	890	Dec 96	Delta II	Mars lander and rover
ACE	NASA	JHU/APL	785	Aug 97	Delta II	Low energy particle
Lunar Prospector	NASA	Lockheed Martin	296	Jan 98	Athena II	Lunar science
DS1	NASA	JPL/Spectrum Astro	486	Oct 98	Delta II	Technology demo
MCO	NASA	JPL/Lockheed Martin	629	Dec 98	Delta II	Mars remote sensing
MPL	NASA	JPL/Lockheed Martin	576	Jan 99	Delta II	Mars science
Stardust	NASA	JPL/Lockheed Martin	385	Feb 99	Delta II	Comet sample return

NASA Earth-Orbiting Small Satellites

Program	Sponsor	Spacecraft Contractor	Launch Mass (kilograms)	Launch Date	Launch Vehicle	Mission
SAMPEX	NASA	NASA GSFC	161	Jul 92	Scout	Science experiments
MICROLAB	NASA/Orbital	Orbital	75	Apr 95	Pegasus	Lightning experiment
METEOR	NASA	CTA (Orbital)	364	Oct 95	Conestoga	Microgravity experiments
TOMS-EP	NASA	TRW	295	Jul 96	Pegasus XL	Ozone mapping
FAST	NASA	NASA GSFC	191	Aug 96	Pegasus XL	Auroral measurements
HETE	NASA	MIT/AeroAstro	128	Nov 96	Pegasus XL	High energy experiments
SAC-B	CONAE/NASA	CONAE	191	Nov 96	Pegasus XL	Science experiments
Seastar	NASA	Orbital	372	Aug 97	Pegasus XL	Ocean color
SNOE	NASA GSFC	LASP	132	Feb 98	Pegasus XL	Space physics
TRACE	NASA	NASA GSFC	250	Apr 98	Pegasus XL	Solar coronal
Clark	NASA	CTA (Orbital)	266	cancelled	Athena I	Science experiments
Lewis	NASA	TRW	385	Jul 98	Athena I	Hyperspectral imaging
SWAS	NASA	NASA GSFC	288	Dec 98	Pegasus XL	Astronomy
WIRE	NASA, JPL	NASA GSFC	255	Mar 99	Pegasus XL	Astronomical telescope
TERRRIERS	NASA, BU	AeroAstro, LLC	288	May 99	Pegasus XL	Space physics
FUSE	NASA, APL	Orbital	1360	Jun 99	Delta II	Space science
QuikSCAT	NASA, NOAA	JPL/Ball Aerospace	870	Jun 99	Titan II	Ocean wind measure
ACRIMSat	NASA, JPL	Orbital	115	Dec 99	Taurus	Sun-Earth atmosphere
IMAGE	NASA GSFC	Lockheed Martin	494	Mar 00	Delta II	Neutral atom/UV measure

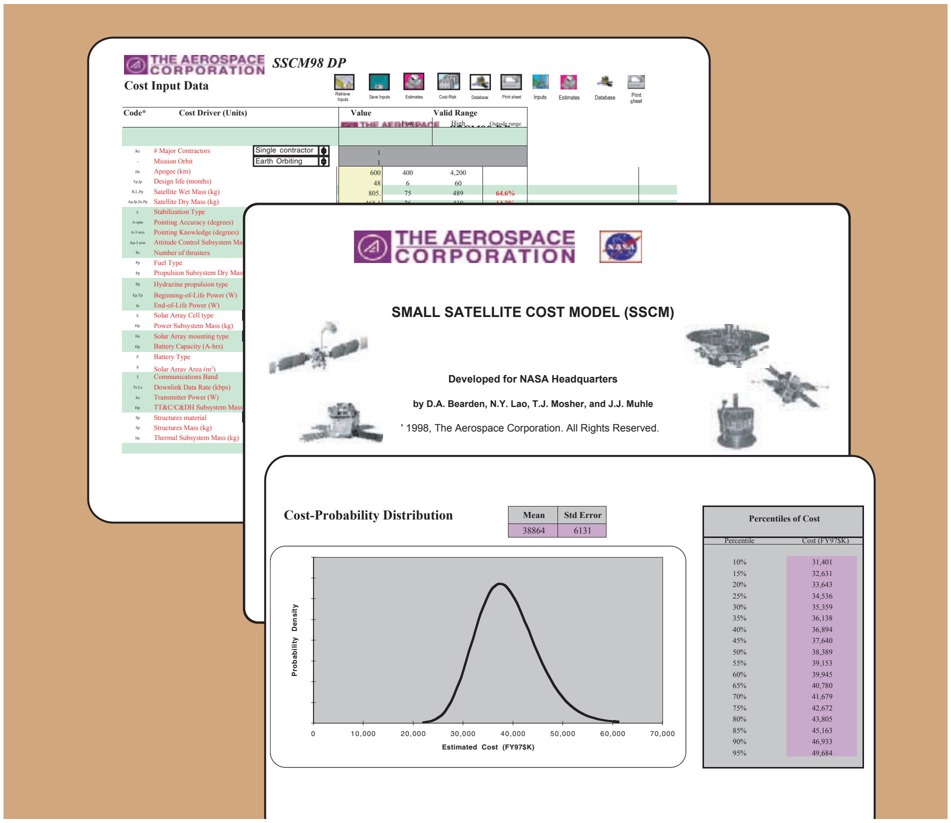
Other U.S.-Built Small Satellites

Program	Sponsor	Spacecraft Contractor	Launch Mass (kilograms)	Launch Date	Launch Vehicle	Mission
GLOMR I	DARPA	DSI (Orbital)	71	Nov 85	Shuttle	Message relay
PEGSAT	DARPA	DSI (Orbital)	68	Apr 90	Pegasus	Message relay
POGS/SSR	STP, ONR	DSI (Orbital)	68	Apr 90	Atlas I	Geomagnetic survey
SCE	ONR	DSI (Orbital)	56	Apr 90	Atlas I	Communications
TEX	STP, ONR	DSI (Orbital)	67	Apr 90	Atlas I	Communications
MACSAT	DARPA	DSI (Orbital)	61	May 90	Scout	Communications
REX	STP	DSI (Orbital)	77	Jun 91	Scout	Radiation
LOSAT-X	SDIO	Ball Aerospace	76	Jul 91	Delta II	Sensor experiments
MICROSAT	DARPA	DSI (Orbital)	26	Nov 91	Pegasus	Communications
MSTI-1	BMDO	JPL/Spectrum Astro	144	Nov 92	Scout	Sensor experiments
ALEXIS	DOE	AeroAstro	113	Apr 93	Pegasus	X-ray mapping
RADCAL	STP, NRL	DSI (Orbital)	91	Jun 93	Scout	Radar calibration tests
DARPASAT	DARPA/AF	Ball Aerospace	161	Mar 94	Taurus	Classified
STEP 0	STP	TRW	489	Mar 94	Taurus	Autonomy experiments
MSTI-2	SDIO	Spectrum Astro	170	May 94	Scout	Sensor experiments
STEP 2	STP	TRW	180	May 94	Pegasus	Signal detect/modulation
STEP 1	STP	TRW	352	Jun 94	Pegasus XL	Atmospheric physics
APEX	STP	Orbital	209	Aug 94	Pegasus	Power experiments
STEP 3	STP	TRW	295	Jul 95	Pegasus XL	Science/communications
REX II	STP	DSI (Orbital)	110	Mar 96	Pegasus XL	Radiation
MSTI-3	SDIO	Spectrum Astro	212	May 96	Pegasus	Hyperspectral imaging
FORTE	DOE	LANL/SNL	210	Aug 97	Pegasus XL	Science
STEP 4	STP	TRW	386	Oct 97	Pegasus XL	Science/communications
GFO	U.S. Navy	Ball Aerospace	357	Feb 98	Taurus	Radar altimetry
MIGHTYSAT	STP	CTA (Orbital)	69	Jul 98	STS/GAS	Science
STEX	NRO	Lockheed Martin	691	Sep 98	Taurus	Tether experiment
TSX-5	BMDO/STP	Orbital	249	Jun 00	Pegasus XL	Remote sensing

- attitude determination and control
- propulsion
- electrical power supply
- telemetry, tracking, and command
- command and data handling
- structure, adapter
- thermal control

Emphasis was placed on obtaining data on spacecraft bus subsystem characteristics. In addition to technical data, costs in the areas of spacecraft integration, assembly and test, program management and systems engineering, and launch and orbital operations were requested.

To gather information on the state of the industry as a whole, as well as specific data, analysts surveyed and interviewed contractors who build small satellites or provide small-satellite facilities (e.g., components, launchers). A cost and technical survey sheet was distributed to virtually every organization and contractor in the small-satellite industry. It was important to obtain information about mass, power, performance, and other technical characteristics because the development of credible subsystem-level cost analyses of small-satellite missions depends on the analyst's ability to relate cost to those characteristics. Programs either already completed or awaiting launch in the next year were targeted.



THE AEROSPACE CORPORATION **SSCM98 DP**

Cost Input Data

Code*	Cost Driver (Units)		Value	Valid Range Low	High	Outside range
Re	# Major Contractors	Single contractor	1			
-	Mission Orbit	Earth Orbiting	1			
He	Apogee (km)		600	400	4,200	
Tp,Ip	Design life (months)		48	6	60	
R,L,Pp	Satellite Wet Mass (kg)		805.	75	489	64.6%
Ap,Ip,Se,Pp	Satellite Dry Mass (kg)					
L	Stabilization Type					
A-spin	Pointing Accuracy (degrees)					
A-3 axis	Pointing Knowledge (degrees)					
Ap-3 axis	Attitude Control Subsystem Ma					
Pe	Number of thrusters					
Pp	Fuel Type					
Pp	Propulsion Subsystem Dry Mas					
Pp	Hydrazine propulsion type					
Ep,Tp	Beginning-of-Life Power (W)					
Ie	End-of-Life Power (W)					
E	Solar Array Cell type					
Hp	Power Subsystem Mass (kg)					
He	Solar Array mounting type					
Hp	Battery Capacity (A-hrs)					
E	Battery Type					
S	Solar Array Area (m^2)					
T	Communications Band					
Te,Le	Downlink Data Rate (kbps)					
Ee	Transmitter Power (W)					
Hp	TT&C/C&DH Subsystem Mass					
Sp	Structures material					
Sp	Structures Mass (kg)					
He	Thermal Subsystem Mass (kg)					

THE AEROSPACE CORPORATION

SMALL SATELLITE COST MODEL (SSCM)

Developed for NASA Headquarters

by D.A. Bearden, N.Y. Lao, T.J. Mosher, and J.J. Muhle

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Cost-Probability Distribution

Mean	Std Error
38864	6131

Percentiles of Cost

Percentile	Cost (FY97$K)
10%	31,401
15%	32,631
20%	33,643
25%	34,536
30%	35,359
35%	36,138
40%	36,894
45%	37,640
50%	38,389
55%	39,153
60%	39,945
65%	40,780
70%	41,679
75%	42,672
80%	43,805
85%	45,163
90%	46,933
95%	49,684

These selected screen shots from the Small Satellite Cost Model demonstrate the parametric cost-estimating model. The model is easy to work with and provides useful outputs such as cost probability distributions.

Because Aerospace operates a federally funded research and development center, it was in a unique position to receive proprietary data from private companies and enter it into a special-purpose database to support government space-system acquisition goals and provide value added to the industry as a whole. Proprietary information delivered to the corporation was treated in a restricted manner, used only for the purpose intended, and not released to organizations, agencies, or individuals not associated with the study team. The information was used exclusively for analysis purposes directly related to cost-model development. Only derived information depicted in a generalized manner was released, and the database itself has remained proprietary. In some cases, formal nondisclosure agreements between the companies and Aerospace were necessary to facilitate delivery of proprietary data.

After properly categorizing cost data, adjusting it for inflation, and breaking it out on a subsystem basis, analysts developed cost-estimating relationships for each of the subsystems, using a subset of the more than 70 technical parameters collected on each of the small satellites. The effort to develop a cost-estimating relationship for a small-satellite subsystem took full advantage of advanced developments in regression techniques. Choosing the proper drivers involved combining a knowledge of statistics, sound engineering judgment, and common sense. Graphics software tools assisted in the development of these cost-estimating relationships, enabling the analyst to view the shape of a function against its data points and to identify the function (whether linear, logarithmic, exponential, or some other form).

The end product was a set of subsystem-level bus-related cost-estimating relationships based entirely on actual cost, physical, and performance parameters of 15 modern small satellites. This was a major advancement over available tools for estimating small-satellite costs. Analysts also developed factors to use in estimating both recurring and nonrecurring costs of bus subsystems, to enable studies of multiple builds—such as the ones that are needed for constellations of small satellites. The cost-estimating relationships enabled the inclusion of cost as a variable in system design tools. They were also incorporated into a stand-alone, menu-driven computerized model that could be distributed to government organizations and private companies that contributed data.

Cost Model Leaves Earth Orbit

In 1996, NASA was moving to smaller platforms for planetary exploration. This movement afforded an important application for the Small Satellite Cost Model. Following well-publicized problems with the Galileo and Mars Observer spacecraft, there had emerged in the early 1990s a growing apprehension in the NASA planetary science community that opportunities for planetary science data return were dwindling. After Galileo was launched in 1989, the next planetary mission scheduled was Cassini, which would launch in October 1997 and begin returning data in 2003, a full six years after Galileo had stopped sending data. Since a steady stream of new data is important to maintaining a vigorous program of planetary and scientific investigation, the situation was naturally a cause for concern. Out of this concern emerged a new NASA small-spacecraft program called Discovery.

The Discovery program's primary goal was to conduct frequent, highly focused, cost-effective missions to answer critical questions in solar-system science. Formally started under NASA's fiscal-year 1994 budget, the Discovery program featured small planetary exploration spacecraft—with focused science goals—that could be built in 36 months or less and would cost less than $150 million (fiscal year 1992), not including the cost of the launch vehicle.

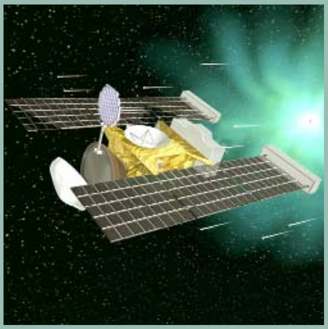
To apply its cost model to this new domain, Aerospace performed, in collaboration with Johns Hopkins University's Applied Physics Laboratory (JHU/APL), a cost-risk assessment of the Near Earth Asteroid Rendezvous (NEAR) mission. This mission, one of NASA's first two Discovery missions, was designed to leave Earth orbit on a trajectory to the near-Earth asteroid Eros. The study identified a number of limitations in applying the Small Satellite Cost Model to interplanetary missions. Out of this information came a concerted effort to gather data on small interplanetary missions to enhance the model. Analysts collected data on missions such as Mars Pathfinder, Lunar Prospector, Clementine, and Stardust, developing cost-estimating relationships appropriate to a Discovery-class mission. Less than a year later the model was again applied successfully to the Near Earth Asteroid Rendezvous spacecraft, demonstrating cost estimates within a few percent of the actual costs.

Once Aerospace demonstrated the ability to assess small interplanetary mission costs, NASA's Langley Research Center Office of Space Science asked the corporation to participate in the Discovery mission evaluation process. Aerospace evaluated 34 Discovery proposals submitted by government, industry, and university teams. These proposals included a wide variety of payloads (including rovers, probes, and penetrators)—more than 120 in all. The goals were to provide independent cost estimates for each proposal, identify cost-risk areas, determine cost-risk level (low, medium, or high) for each proposal, and evaluate proposals in an efficient and equitable manner. Five finalists were selected.

In 1997, as a follow-on to the successful Discovery mission evaluation, the NASA Office of Space Science asked Aerospace to assist in the selection of Small Explorer missions. This was a series of small, low-cost interplanetary and Earth-orbiting science missions designed to provide frequent investigative opportunities to the research community. Aerospace served on the Technical, Management, and Cost review panel. Fifty-two Small Explorer mission concepts were evaluated, from which two final missions were chosen.

NASA commended Aerospace for its work on Discovery and Small Explorer missions. Because of the work it had done on these programs, Aerospace was invited to participate in a National Research Council workshop, from which a report titled "Reducing the Costs of Space Science Research Missions" was generated. Aerospace was also invited to join the editorial board of a new international peer-reviewed technical journal (*Reducing Space Mission Cost*, published by Kluwer Academic Publishers) and to become a member of the Low Cost Planetary Missions Subcommittee of the International Academy of Astronautics Committee on Small Satellite Missions.

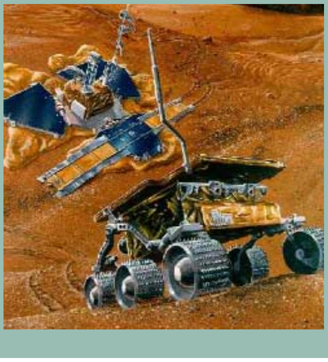
Missions Evaluated by the Small Satellite Cost Model



Launched in February 1999, **Stardust** is journeying to the comet Wild-2. It will arrive in 2004 and, during a slow flyby, will collect samples of dust and gas in a low-density material called aerogel. The samples will be returned to Earth for analysis in 2006. Stardust will also photograph the comet and do chemical analysis of particles and gases. The JPL/Lockheed Martin-built spacecraft is one of NASA's Discovery Program missions. It is the first NASA mission dedicated to exploring a comet and the first U.S. mission launched to robotically obtain samples in deep space.

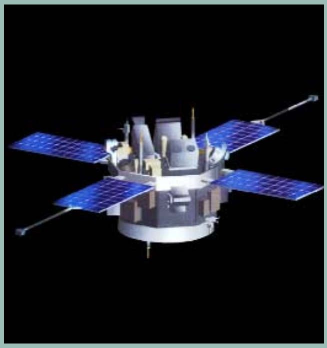
NEAR was launched in February 1996. Its objective was to orbit the asteroid Eros for one year starting in January 1999, collecting scientific data. Developed in 29 months at JHU/APL, NEAR was part of the NASA Discovery Program. Its payload was composed of a multispectral imager, a laser rangefinder, an X-ray/gamma-ray spectrometer, and a magnetometer. A software-error-induced burn abort that occurred in December 1998 resulted in delaying the rendezvous and subsequent data acquisition until February 2000.

The **Lunar Prospector**, a NASA-sponsored lunar polar orbiting probe developed by Lockheed Martin, was launched aboard Athena II in January 1998. Its primary mission was to map the moon's chemical, gravitational, and magnetic properties. Data from instruments, including a gamma-ray spectrometer, a neutron spectrometer, an alpha particle spectrometer, a magnetometer, and an electron reflectometer, were used to construct a map of the surface composition of the moon.



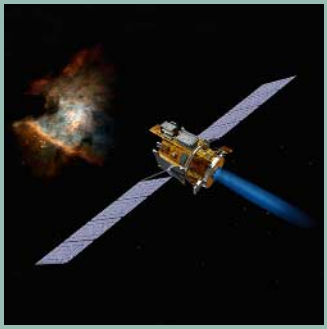
Mars Pathfinder, the second launch in the Discovery Program developed by JPL, consists of a cruise stage, entry vehicle, and lander. The mission of Mars Pathfinder was to test technologies in preparation for future Mars missions, as well as to collect data on the Martian atmosphere, meteorology, surface geology, and rock and soil composition. On July 4, 1997, Mars Pathfinder successfully landed on Mars and subsequently rolled out the Sojourner rover to analyze native rock composition.

Illustrations courtesy of NASA

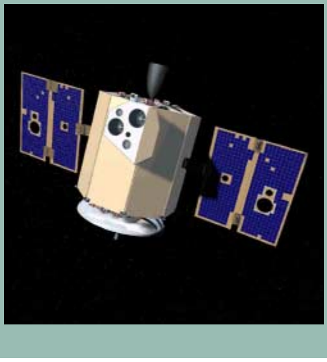


The **ACE** (Advanced Composition Explorer) spacecraft carried six high-resolution sensors, mainly spectrometers, and three monitoring instruments. It collected samples of low-energy solar and high-energy galactic particles and measured conditions of solar wind flow and particle events. An Explorer mission sponsored by the NASA Office of Space Science and built by JHU/APL, ACE orbits the L1 libration point, a location 900,000 miles from Earth where the gravitational effects of Earth and the sun are balanced, to provide near-real-time solar wind information.

SWAS (Submillimeter Wave Astronomy Satellite) was the third NASA Small Explorer mission. It was launched aboard a Pegasus XL rocket in December 1998. The overall goal of the mission was to understand star formation by using a passively cooled Cassegrain telescope to determine the composition of interstellar clouds and establish the means by which these clouds cool as they collapse to form stars and planets. SWAS observed water, molecular oxygen, isotopic carbon monoxide, and atomic carbon.



Launched in October 1998, **DS1** (Deep Space 1) was a NASA New Millennium Program mission. Its objective was to validate several technologies in space including solar electric propulsion and autonomous navigation. Instruments on board included a solar concentrator array and a miniature integrated camera and imaging spectrometer. The spacecraft, built by JPL and Spectrum Astro, was designed to monitor solar wind and measure the interaction with targets during flybys of an asteroid and a comet.



The primary mission objectives of the **Clementine** lunar orbiter, launched in January 1994 aboard Titan IIG, were to investigate long-term effects of the space environment on sensors and spacecraft components and to take multispectral images of the moon and the near-Earth asteroid Geographos. The Naval Research Laboratory-built spacecraft incorporated advanced technologies, including Lawrence Livermore National Laboratory lightweight sensors. After Clementine completed lunar mapping, its onboard computer malfunctioned on departure from lunar orbit and depletion of onboard fuel resulted.

Examining the Faster-Better-Cheaper Experiment

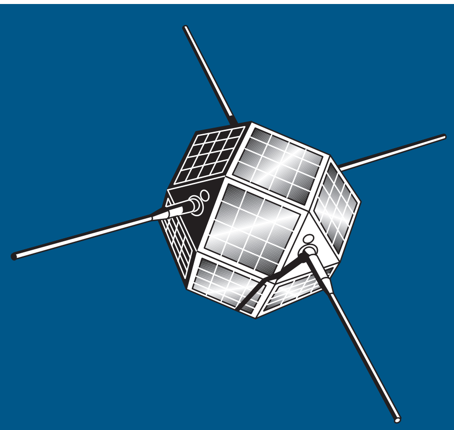
Successful NASA programs such as the Mars Pathfinder and the Near Earth Asteroid Rendezvous mission effectively debunked the myth that interplanetary missions could only be accomplished with billion-dollar budgets. They set a new standard against which all later missions were not only forced to measure up but go beyond. Designers were asked to meet unrelenting mission objectives within rigid cost and schedule constraints in an environment characterized by rapid technological improvements, immense budgetary pressure, downsizing government, and distributed acquisition authority.

As a result of these constraints, NASA had greatly increased its utilization of small spacecraft to conduct low-cost scientific investigations and technology demonstration missions. The original tenets of the small-satellite paradigm, including low cost, maximum use of existing components and off-the-shelf technology, and reduced program-management oversight and developmental effort, had been applied to increasingly more ambitious endeavors with increasingly demanding requirements. This move had clearly benefited the scientific community by greatly diversifying the number and frequency of science opportunities.

A number of failed small scientific spacecraft, however, such as Small Satellite Technology Initiative's Lewis and Clark, and the Wide-field Infrared Experiment, fueled an ongoing debate on whether NASA's experiment with faster-better-cheaper missions was working. The loss of the Mars Climate Orbiter and the Mars Polar Lander within a few months of each other sent waves of anxiety throughout government and industry that the recipe for successful faster-better-cheaper missions had been lost. Impaired missions or "near misses," such as the Mars Global Surveyor, contributed to the debate as well, and many wondered whether programs currently on the books or late in development were too ambitious for the time and money they had been allotted.

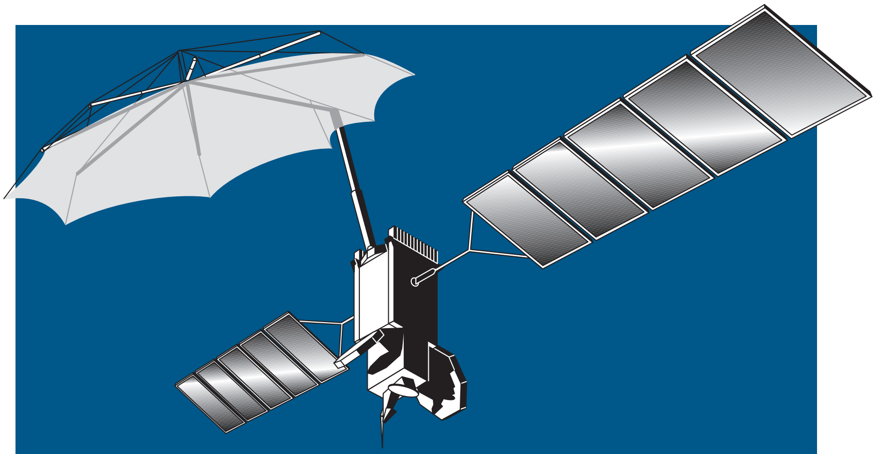
At the heart of the matter was allocation of cost and schedule. Priorities had changed. During the last few years the traditional approach to spacecraft design, driven by performance characteristics and high reliability to meet mission objectives, had completely given way to developments dominated by cost- and schedule-related concerns. While it was readily apparent that the faster-better-cheaper strategy resulted in lower costs per mission and shorter absolute development times, these benefits may have been achieved at the expense of reduced probability of success. Some questions lingered. When was a mission too fast and too cheap with the result that it was prone to failure? Given a fixed amount of time and money, what level of performance and technology requirements would cause a mission to stop short of failure due to unforeseen events?

Risks often do not manifest ahead of time or in obvious ways. However, when examined after the fact, mission failure or impairment is often found to be the result of mismanagement or miscommunication in fatal combination with a series of low-probability events. These missteps, which often occur when a program is operating near the budget ceiling or under tremendous schedule pressure, result in failures caused by lack of sufficient resources to



Low-Complexity Spacecraft
Complexity index 0–0.33

- Small payload mass (~5–10 kilograms)
- One payload instrument
- Spin or gravity-gradient stabilized
- Body-fixed solar cells (silicon or gallium arsenide)
- Short design life (~6–12 months)
- Single-string design
- Aluminum structures
- Coarse pointing accuracy (~1–5 degrees)
- No propulsion or cold-gas system
- Low-frequency communications
- Simple helix or patch low-gain antennas
- Low data rate downlink (~1–10 kilobits per second)
- Low power requirements (~50–100 watts)
- No deployed or articulated mechanisms
- Little or no data storage
- No onboard processing (“bent-pipe”)
- Passive thermal control using coatings, insulation, etc.



High-Complexity Spacecraft
Complexity index 0.67–1

- Large payload mass (~200–500 kilograms)
- Many (5–10) payload instruments
- Three-axis stabilized using reaction wheels
- Deployed sun-tracking solar panels (multijunction cells or concentrator)
- Long design life (~3–6 years)
- Partially or fully redundant
- Composite structures
- Fine pointing accuracy (~0.01–0.1 degrees)
- Monopropellant or bipropellant system with thrusters (4–12)
- High-frequency communications
- Deployed high-gain parabolic antennas
- High data rate downlink (thousands of kilobits per second)
- High power requirements (~500–2000 watts)
- Deployed and/or articulated mechanisms
- Solid-state data recorders (up to 5 gigabytes)
- Onboard processing (up to 30 million instructions per second)
- Active thermal control using heat pipes, radiators, etc.

thoroughly test, simulate, or review work and processes.

Having maintained an extensive historical database of programmatic information on NASA faster-better-cheaper missions to support the Small Satellite Cost Model development, Aerospace was well positioned to examine the situation. With a decade of experience and more than 40 scientific and technology demonstration spacecraft flown, sufficient information existed for use in conducting an objective examination. To understand the relationship between risk, cost, and schedule, Aerospace analyzed data for missions launched between 1990 and 2000, using technical specifications, costs, development time, and operational status.

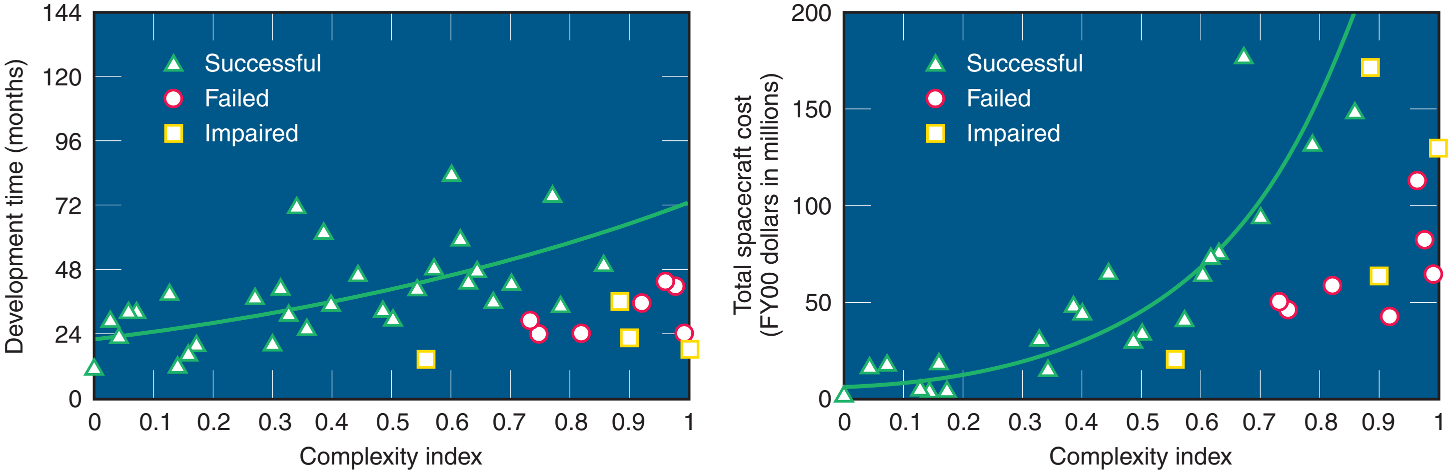
The study examined the faster-better-cheaper strategy in terms of complexity measured against development time and cost for successful and failed missions. The failures were categorized as partial, where the mission was impaired in some way; catastrophic, where the mission was lost completely; or programmatic- or launch-related, where the mission was never realized because of cancellation or failure during launch.

A complexity index was derived from performance, mass, power, and technology choices, as a top-level representation of the system for purposes of comparison. Complexity drivers (a total of 29) included subsystem technical parameters (such as mass, power, performance, pointing accuracy, downlink data rate, technology choices) and a few general programmatic factors such as heritage (reuse of a part that flew on a previous mission) and redundancy policy. The process used to estimate spacecraft complexity included the following steps.

- Identify parameters that drive or significantly influence spacecraft design.
- Quantify the parameters so that they can be measured.
- Combine the parameters into an average complexity index (expressed as a value between zero and one).

To determine whether the faster-better-cheaper experiment was successful, analysts plotted a comparison of complexity relative to development time and cost, noting failures. Some interesting trends emerged. Correlation between complexity, cost, and schedule was evident. A threshold, or “no-fly zone,” was apparent where project resources (time, funds) were possibly insufficient relative to the complexity of the undertaking. While it is unknown whether allocation of additional resources would have increased the probability of success of a given mission, this much is clear: When a mission fails or becomes impaired, it appears that it is too complex relative to its allocated resources.

The observation of a correlation between cost and development time and complexity, based on actual program experience (i.e., actual costs incurred and development time required as opposed to numbers used during the planning phase), is encouraging because this model can be applied to future systems. The index may



Cost and schedule plotted against a complexity index derived from performance, mass, power, and technology choices. The regression curves may be used to determine the level of complexity possible for a set budget or development time. Although the complexity index does not identify the manner or subsystem in which a failure is likely to occur, it does identify a regime by which an index calculated for a mission under consideration may be compared with missions of the recent past.

reveal a general risk of failure, but it won't necessarily specify which subsystem might fail or how it will fail. Nevertheless, it does identify when a new mission under consideration is in a regime occupied by failed or successful missions of the recent past. This process should allow for more informed overall decisions to be made for new systems being conceived.

Conclusion

In summary, early small-satellite studies showed that older cost-estimation models based on historical costs and technical parameters of large satellite systems could not be successfully applied to small systems. It was necessary to develop a model that would be tailored specifically to this new category of spacecraft. To this day, there remains no formally agreed-upon definition of "small spacecraft," although such spacecraft are typically considered to be Discovery-class in size or less (i.e., for interplanetary applications, they fit on a Delta II launch vehicle; for Earth-orbiting applications, they weigh less than 500 kilograms), and most are budgeted in the $50- to $250-million range.

Aerospace has been studying small satellites since 1991, and the main product of its ongoing work is the Small Satellite Cost Model. Based on actual physical and performance parameters of small Earth-orbiting and interplanetary spacecraft flown during the last decade, this software tool was developed to estimate the cost of a small spacecraft. It has addressed many of the questions that were originally raised about cost estimation for small systems. The model is used in assessment of small-satellite conceptual designs, technology needs, and capabilities, and it is continually updated to model state-of-the-art systems.

The Small Satellite Cost Model has developed through several generations, with additions to the database and improvements to the cost-estimating relationships serving as the primary drivers from version to version. Currently, the small-satellite database has evolved to include more than 40 programs. While initial small-satellite studies were funded by DOD and Aerospace internal funds in the early 1990s, the development of Small Satellite Cost Model version 1.0 was funded by NASA in 1995. The database and model were updated in 1996 (version 2.0), and interplanetary capabilities were added in 1998 (version 3.0 or Small Satellite Cost Model 98). The fourth release is now in development.

A version of the model is supplied to industry members who provide data that can improve it. There is also a publicly available version (see www.aero.org/software/sscm). The model is used extensively by DOD, JPL, and virtually all of the NASA field centers. It has become the standard for parametric evaluation of small missions worldwide and is used by the European Space Agency and the French Centre National d'Etudes Spatiales, among other organizations. A number of foreign-built small spacecraft are included in the database.

The most recent application of the small-satellite study is the assessment of NASA's approach, under constrained budgets and rigid schedules, to conduct faster-better-cheaper scientific investigations. Recent instances of failed or impaired spacecraft have brought into question the faster-better-cheaper strategy, especially for interplanetary applications. While missions have been developed under this strategy with lower costs and shorter development times, these benefits have, in some cases, been achieved at the expense of increasing performance risk. Addressing the question of when a mission becomes "too fast and too cheap" with the result that it is prone to failure, studies have found that when a mission's complexity is too great relative to its allocated resources, it fails or becomes impaired.

Aerospace's Small Satellite Cost Model has been highly successful, as evidenced by NASA's recognition for the model's application in the Discovery and Small Explorer programs. A critical component of many small-satellite evaluation activities and a major contribution to the space industry as a whole, the model is a stellar example of the value-added role Aerospace can play. There is every reason to expect that more success stories will be forthcoming.

Further Reading

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The History Behind Small Satellites

The Soviet Union's October 1957 launch of Sputnik, the first satellite, stunned the world. It kicked off the "space race" between the Soviet Union and the United States, and in doing so, changed the course of history. Space would become an important setting in which nations could demonstrate political and scientific prowess. The United States responded to Sputnik in January 1958, launching Explorer I, a simple, inexpensive spacecraft built to answer basic questions about Earth and near space.

Explorer and its immediate descendants were small satellites, but only because of launch-vehicle limitations. Size and complexity of later spacecraft grew to match launch capability. Not surprisingly, the early years of the space race saw U.S. projects expand on many levels. The Cold War spurred the buildup of a massive space-based defense and communications infrastructure in the United States. The government and its contractors, essentially unchecked by budgetary restrictions, developed large, sophisticated, and expensive platforms to meet increasingly demanding mission requirements. NASA followed the lead of DOD, building complex scientific and interplanetary spacecraft to maximize research capabilities.

U.S. expertise in space science was escalating. Launch-vehicle capability continued to grow from the 1960s through the early 1980s, with large satellite platforms carrying more powerful payloads (and, often, multiple payloads). Engineers and scientists worked to perfect the technologies necessary for mission success and lengthier operations. Major research spacecraft took nearly a decade to develop, and they grew to cost more than $1 billion.

As years passed, however, several factors pointed to a need to scale back. With the end of the Cold War, government spending in science and technology received increased public scrutiny. Funding for large, complex flagship missions would no longer be available. Budget constraints forced program managers to look seriously at smaller platforms in an attempt to get payloads onto less-costly launch vehicles.

At the same time, the public voiced a growing concern over the potential for reduced research findings in the wake of several failures of large, high-profile, expensive NASA missions; for example, a crippling manufacturing defect was discovered on the Hubble Space Telescope. NASA came under fire for its perceived inability to deliver quality scientific research.

The scientific community expressed frustration about the lack of flight opportunities because only a few flagship missions, with decade-long development times, were being undertaken. After the limited-capability launch of Galileo in 1989 and the loss of Mars Observer in 1993, the next planetary mission to be launched was the Cassini mission to Saturn in 1997, which wouldn't start transmitting data to Earth until 2003, six years after Galileo stopped sending data from Jupiter.

All these issues—budgetary changes brought about by the end of the Cold War, mission failures, predicted gaps in scientific data return—meant that future space-science research and planetary exploration would require a different approach.

In the mid-1980s, with new developments in microelectronics and software, engineers could package more capability into smaller satellites. Funding from the DOD Advanced Research Projects Agency, the Air Force Space Test Program, and university laboratories allowed engineers to build low-profile, low-cost satellites with maximum use of existing components and off-the-shelf technology and minimal nonrecurring developmental effort. Research organizations, private businesses, and academic institutions—all weary of waiting years for their instruments to be piggybacked on large satellites—began to develop small satellites that could be launched as secondary payloads on the shuttle or large expendable boosters.

Small space systems were emerging that were affordable and easy to use, and thus attractive to a larger, more diverse customer base. A new trend had taken shape, and a whole new era in the history of space science was beginning.

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