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FASTER, BETTER, CHEAPER: AN INSTITUTIONAL VIEW

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ABSTRACT

The focus in solar system exploration has shifted to a "faster, better, cheaper" approach featuring focused, technically sophisticated, fast track missions. To implement this approach, the Jet Propulsion Laboratory (JPL) has modified its management practices and its developmental process and tools. This paper examines the challenges, responses, and early results of this new way of doing business. The focus of this evaluation is at the institutional rather than the project level; that is, how is JPL managing a suite of many small missions rather than a few big ones?

Current JPL missions are designed to fixed cost targets that are an order of magnitude lower than their predecessors. They have focused scientific objectives, are usually part of an ongoing program of related missions, and are being developed in about half the time previously allowed. They utilize new technology to reduce mass and improve performance.

The Laboratory has responded to the challenges of the new approach with modern design and development practices and information technologies, which result in an interdependence and need for resource sharing at many levels — project to project, organization to organization, and nation to nation.

The early results are encouraging. Eight missions developed under the new paradigm have been launched from 1997 to 1999, with a wide range of destinations and objectives. The program architecture concept has proven to be a robust one. While many implementation issues still need to be resolved, progress is being made and the resilience of the underlying architecture has been validated.

INTRODUCTION

The robotic exploration of space may be thought of as proceeding in three phases.[1] The first phase was focused on getting there, by overcoming the engineering challenges of reaching and operating in an unfamiliar environment. In planetary exploration, this was the era of the reconnaissance fly-by mission. The second phase was devoted to finding out what was there. Since the solar system was unexplored territory, missions were loaded with a full range of scientific instrumentation. Flight systems such as Voyager, Galileo, and Cassini were large and complex. Project development cycles were long, and mission costs could exceed a billion dollars. The third phase, which we have now entered, is devoted to understanding what is there. To achieve this end, frequent missions with ambitious but clearly focused objectives are needed. These missions emphasize specific destinations, *in situ* exploration, and sample returns; broader environmental surveys are obtained by linking sets of missions.

At JPL, this third era can be considered to have begun with the Mars Pathfinder project, a NASA Planetary Discovery mission that reached the surface of Mars in July 1997. To achieve the objectives of the third phase of exploration, this flight system and those that followed it had to be frequent, highly capable, and affordable. In other words, faster, better, and cheaper (FBC). In testimony to Congress, the NASA Administrator illustrated this point with the data shown in Figure 1, comparing the cost of the Galileo Jupiter orbiter and probe with that of eleven subsequent FBC planetary missions.[2]

Let's further define faster, better, cheaper in the context of this paper, which addresses JPL's mission of robotic space exploration. Faster applies to project development time, which for convenience can be defined as the period from project approval to launch. Rapid development cycles help control costs and enable the incorporation of the latest advances in technology, because the design freeze date is closer to the launch date. Better applies to the capability of the flight system as a scientific instrument. Improvement here is based on the use of advanced technologies, and on better-focused science based on the knowledge gained from earlier exploration missions. Finally, cheaper denotes both lower cost per mission and, through clever design and use of technology, more effective use of available funds. As noted earlier, schedule control and closely tailored mission objectives contribute to this end. Advanced technologies not only contribute to improved performance, but they can also be used to reduce the mass of flight systems, thereby reducing launch costs.

The flight systems of the third era must therefore be lightweight, highly capable, affordable, and amenable to rapid development. Focused mission objectives and modern technologies alone will not be enough to achieve the ambitious third era objectives within the constraints of a fixed budget. We must also improve the way we develop and fly these missions. The demands of the first and second eras led JPL to optimize our implementation approach and infrastructure on a mission-by-mission basis. As we shall see, significant changes are needed for the third era.

A time-honored approach to meeting demands such as these is the creation and use of a "skunk works," made famous by Kelly Johnson of Lockheed Aircraft. It features the use of talented collocated and dedicated teams, freed

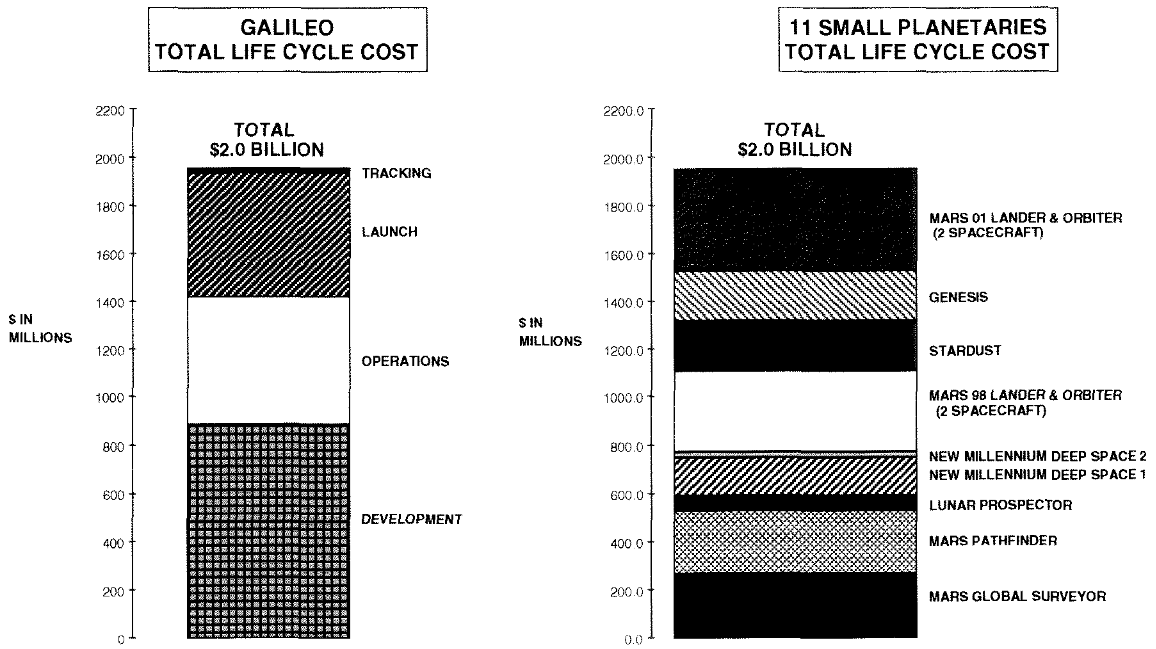


Figure 1. Galileo vs. New Small Planetary Missions

of the conventional rules of corporate bureaucracy. This approach optimizes very effectively around a specific local goal. Replication of this model of independence on a corporate scale, however, would miss the economies available from pooled resources and standard processes. Our challenge, then, and the subject of this paper, is how best to deliver on the demands of FBC on a global scale over the long haul.

THE NEW ERA OF SPACE EXPLORATION

The flight missions undertaken to date in the FBC mode offer both an illumination of the demands of the approach and some valuable lessons learned on how to meet those demands. Figure 2 is a composite portrait of these missions, and Table 1 gives mission descriptions. These missions are in a sense transitional, carried out in a learn-as-you-go and improve-as-you-learn mode.

The mission results to date are encouraging. With the exception of WIRE and MCO, mission objectives to date have been achieved. Cycle time and mission costs are down. The staffs of JPL and its industrial, academic, government, and international partners have stepped up to the challenge with creativity and determination, and often with heroics. This has proven to be a rich learning environment, but its success has depended on the willingness of talented people to work longer and harder than they should. Better ways of doing things are clearly needed. Lessons learned cited by the project managers are summarized in Table 2. Note that these maxims are not in themselves revolutionary, but are consistent with the management practices of capable and experienced team leaders in other environments. The WIRE and MCO mission failures illustrate the importance of following—not abandoning—a disciplined approach to design, evaluation, test, and operations of flight systems. In the case of WIRE the premature deployment of the telescope cover that led to mission failure was caused by faulty electronics design that should have been caught with adequate peer review and system test. The MCO spacecraft loss is still under investigation.

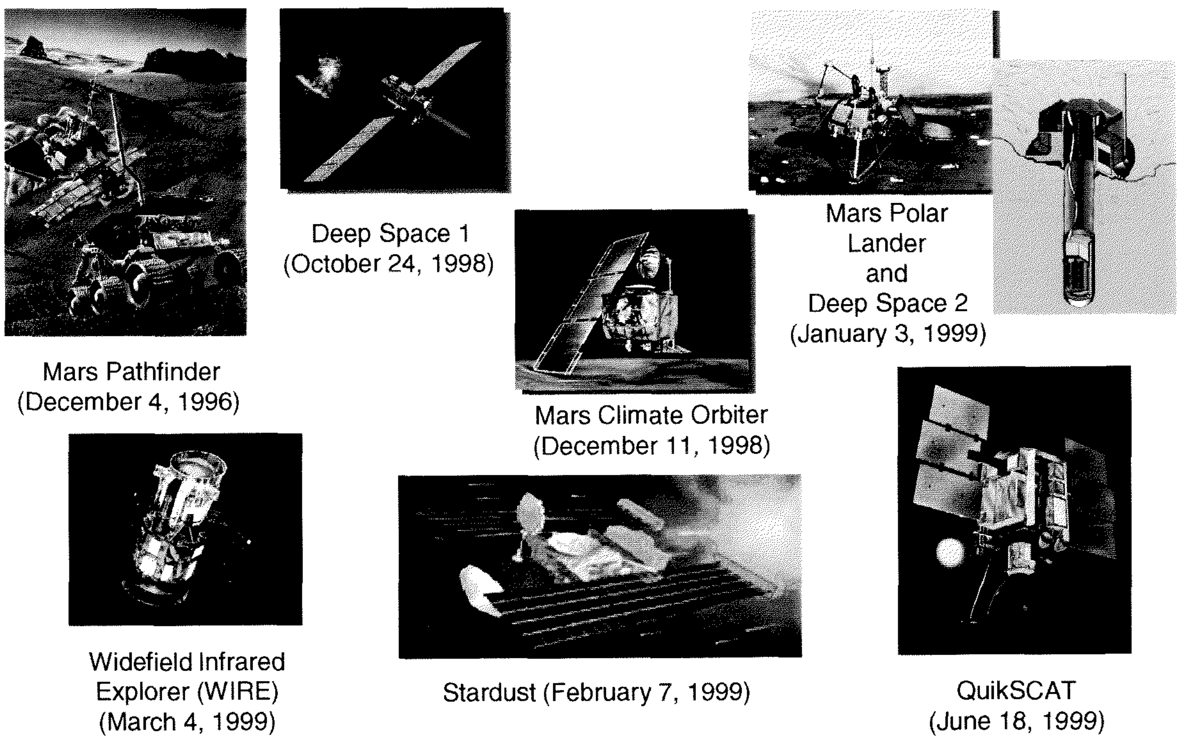


Figure 2. Faster-Better-Cheaper: Missions to Date

Table 1. Faster, Better, Cheaper Missions to Date

Mission	Launch Date/ Launch Vehicle	Target	Arrival	Mission Cost ($M)	Notes
Mars Pathfinder	December 4, 1996 Delta II 7925	Mars	July 4, 1997	$225	Lander and Sojourner Rover. Discovery series.
Deep Space 1	October 24, 1998 Delta II 7326	Asteroid 1992KD	July 28, 1999	$124	Technology testbed. New Millennium series.
Mars Climate Orbiter	December 11, 1998 Delta II 7425	Mars orbit	September 23, 1999	$95	Mars Surveyor series. Lockheed Martin prime, JPL navigation lead. Mission lost due to Mars atmosphere entry.
Mars Polar Lander	January 3, 1999 Delta II 7425	Mars south polar cap	December 3, 1999	$143	Mars Surveyor series. Lockheed Martin prime.
Deep Space 2	January 3, 1999 Delta II 7425	Mars south polar layered terrain	December 3, 1999	$31	Penetrator carried by Mars Polar Lander. New Millennium series.
Stardust	February 7, 1999 Delta II 7426	Comet Wild-2	January, 2004	$110	Sample return January 2006. Lockheed Martin prime. Discovery series.
Widefield Infrared Explorer (WIRE)	March 4, 1999 Pegasus XL	Starburst galaxies	—	$26	GSFC mission, JPL payload. Mission lost due to payload electronics design error.
QuikSCAT	June 18, 1999 Titan II	Earth—ocean wind data	—	$67	JPL mission and payload. GSFC/Ball spacecraft. 12 months from project approval to launch readiness.

GETTING IT DONE

At the institutional level, JPL has responded to the challenge of managing a suite of FBC missions by reorganizing the work, by reengineering the design and development process, by providing supportive tools and work environment, by creating domestic and international partnerships, and by looking to the future while addressing the problems of the present.

Organizational and Architectural Considerations

The focused missions of the FBC era have been organized by NASA into ongoing programs with periodic flights. This program continuity offers the opportunity to optimize individual flights around an overall mission objective, maximizing commonality of flight systems and grouping related flights under a single management structure to reduce costs.

A good example of this approach is that of the Mars Sample Return mission, which uses a number of collaborative flight systems to achieve a single mission objective. Figure 3 is a schematic representation of the mission architecture. In 2003, the first sample-collecting rover will be sent to Mars; the rover will analyze rocks, and take samples of the most interesting ones. In 2005, another lander and rover will be sent to retrieve samples from another site. Using a small Mars Ascent Vehicle, the samples will be launched into Mars orbit. A separate sample return spacecraft will rendezvous with the rock caches orbiting Mars, and return the samples to Earth in 2008 for detailed analysis.

In addition to reorganizing along program lines, a number of functions previously carried out within the body of the projects are now carried

Table 2. Lessons Learned on Missions to Date

Partnering with Others	• Successful implementation requires sufficient staff with expertise to both perform and review the product • Know the contractor's capabilities and limitations • Contracts still need Quality Assurance oversight
Startup Considerations	• Timely staffing of key positions is important to success • An adequate pre-project phase is critical
Managing Resources	• Establish robust margins for mass, power, funds, memory and schedule • Adjust allocations based on risk • Manage reserves aggressively • Software dominates risk issues • System Engineering is not a title—it's a function • Money spent on team building and employee recognition is money well spent • Money spent on Quality Assurance is money well spent
Staffing and Human Factors	• Timely and stable staffing of key positions is critical • Most project staff are highly motivated and dedicated, and will strive to deliver a quality product at any cost • Humane planning and management is needed to avoid continuous overwork
The Project Environment	• Contributions of talented people and their commitment to the project in a team environment is the #1 key to success • An atmosphere of open, honest and direct communication is essential • Sensible co-location encourages communication
Peer Review	• Early and often • By people who have been there/done that
Test, Test, Test	• Test like you fly • Fly like you test

out as a separate program, with deliverables to the projects. Notable among these is technology development. Cassini flew a number of technical advancements for the first time, including a lightweight deep space transponder, radiation hardened computer, and advanced gyroscope. These flight proven features were then passed on to subsequent missions. Indeed, the current generation of FBC missions have benefited greatly from this legacy, as is illustrated in Figure 4.

FBC missions, however, have neither the time nor the resources to bring new technologies to flight readiness. Applied technology development has therefore been moved out of the developmental projects themselves into ongoing programs focused on delivering needed technologies to the projects in flight ready condition. There are three organizational models for such linked technology development at JPL. In the first, an ongoing program provides periodic deliveries to the projects as needed. The Deep Space Systems Technology Program (also known as X2000) is such a program. Figure 5 illustrates the technologies to be delivered by the X2000 Program. The Program consists of two major pieces:

- Technology Planning, Fusion, and Development. This includes technology development in avionics, communications, and power systems. In addition, technology developed in other programs (both NASA and non-NASA) are fused with the internally developed technology. About every three years, a set of technologies that are likely to mature in the next few years is assembled into a Delivery.
- Deliveries. Each delivery is aimed at a large set of science mission customers. Each delivery provides an integrated generic capability. Deliveries are managed at JPL like flight projects. This means that customers can plan to use the output of these deliveries—even in their critical path towards launch.

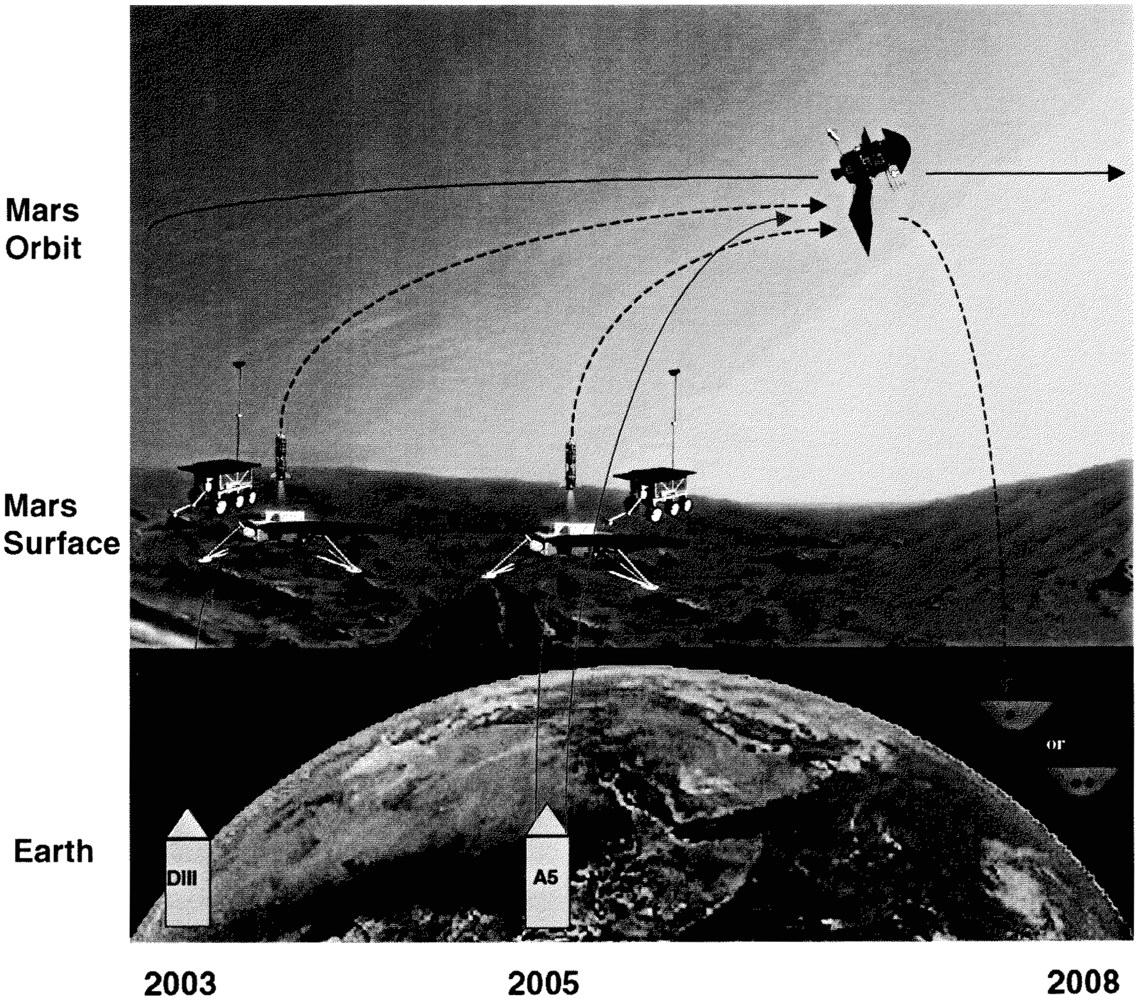


Figure 3. Mars Sample Return Missions

In the second technology development model, needed advances are planned into a sequenced series of flight missions, with each mission building on the past in order to reach a powerful new capability. The Origins Program uses such an approach in developing space-based optical interferometry, as illustrated in Figure 6.

In the last organizational model, attention is focused on flight validation. While programs such as Exploration Technology and X2000 develop and deliver needed technologies, a companion program—the New Millennium program—tests and validates these technologies. By testing advanced technologies now, the New Millennium program expects to lower the risk that future missions incur in using these technologies.

Each New Millennium mission demonstrates a different set of technologies. As shown in Figure 7, the first mission, Deep Space 1 (DS-1) tested 12 new technologies, including autonomous operation, ion propulsion, and advanced power, telecommunications, electronics, structures, and scientific instrument demonstrations. Deep Space 2 will provide flight validation of an instrumented soil penetrator. Future New Millennium flights will validate technologies targeted for both near Earth and deep space future missions.

In order to create and nourish the capabilities to develop and implement these technologies, JPL has created internal cross-organizational Centers of Excellence. These Centers receive special attention in strategic resource allocations

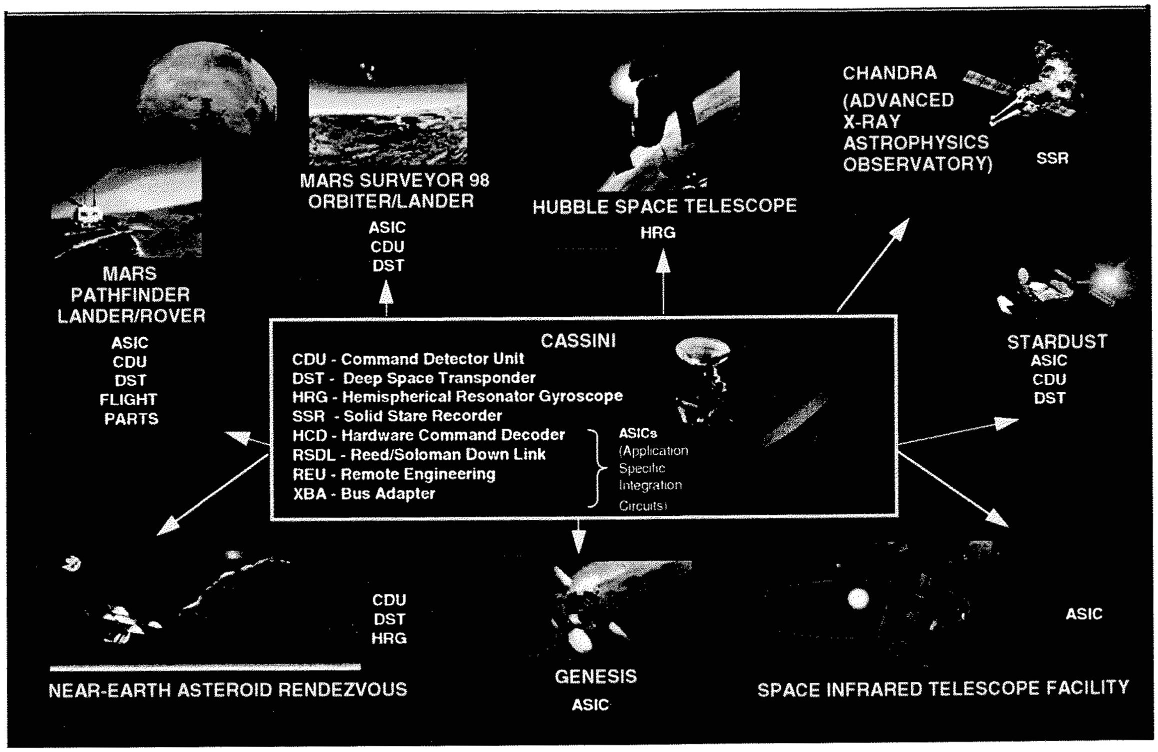


Figure 4. Cassini's Legacy: Reducing the Cost and Risk for Future Missions

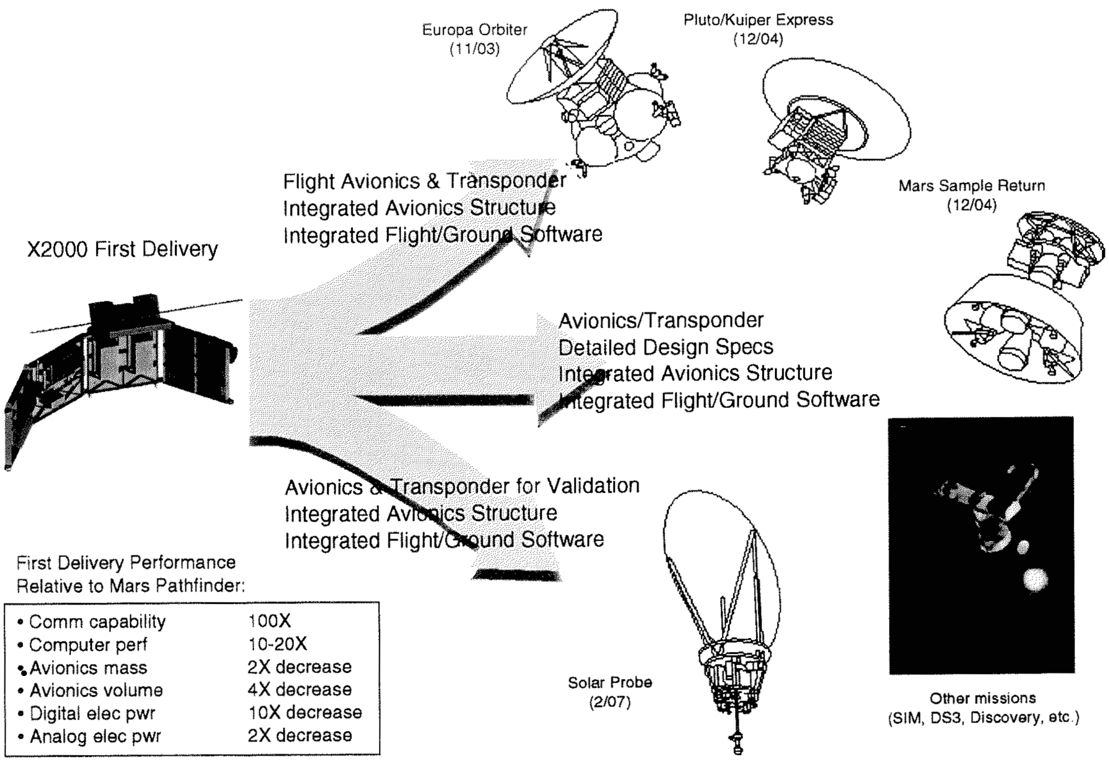


Figure 5. X2000: Enabling Near-Term Missions

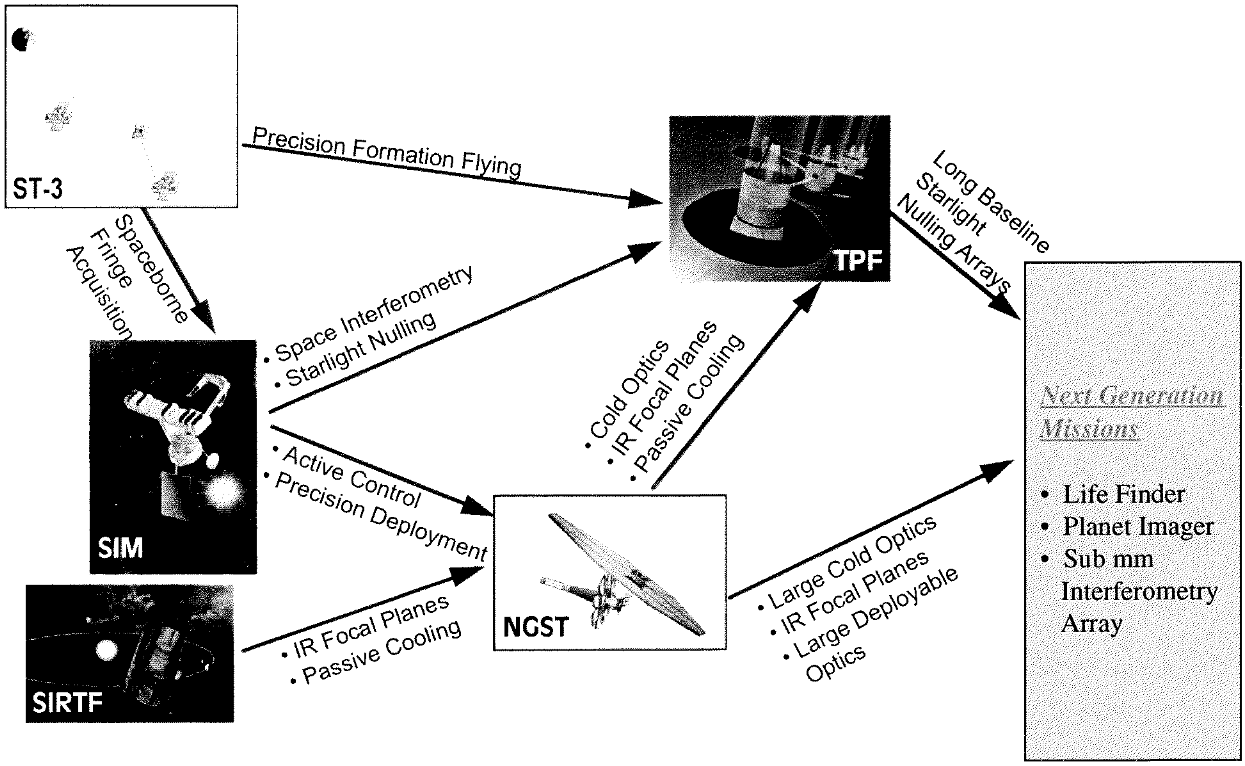


Figure 6. Origins—A Program of Scientifically and Technologically Linked Missions

(workforce, partnership, facilities, tools development, and funding). Current JPL Centers of Excellence include:

- Interferometry
- *In Situ* Exploration and Sample Return
- Space Microelectronics Technology
- Integrated Space Microsystems
- Spacecraft Mission Architecture and Design
- Deep Space Communications and Navigation Systems
- Space Mission Information and Software Systems.

Process Reengineering

The organizational issues discussed above are interrelated with the way in which work is carried out, that is, to the underlying design and development processes. Beginning in 1995, JPL undertook the reengineering of several core business processes, including the processes that produce its flight and related ground systems.[3] The latter effort was entitled the Develop New Products (DNP) reengineering project. DNP was to be an integrated set of processes, tools, and facilities that would enable JPL to rapidly conceive, develop, and fly highly advanced space systems. The "products" would include spacecraft, instruments, and operations systems. The DNP goal was to produce a product in half the time and two-thirds the cost previously attainable through the use of integrated product development teams, concurrent engineering, and model- and simulation-based design and development. This effort is supported by complementary models, tools, information systems, facilities, and training courses. There are currently three main operational DNP facilities:

The Flight System Testbed (FST) was established in 1993. The primary function of the FST is to support project system software development and system or subsystem level testing. The projects can verify system design decisions and subsystem or instrument

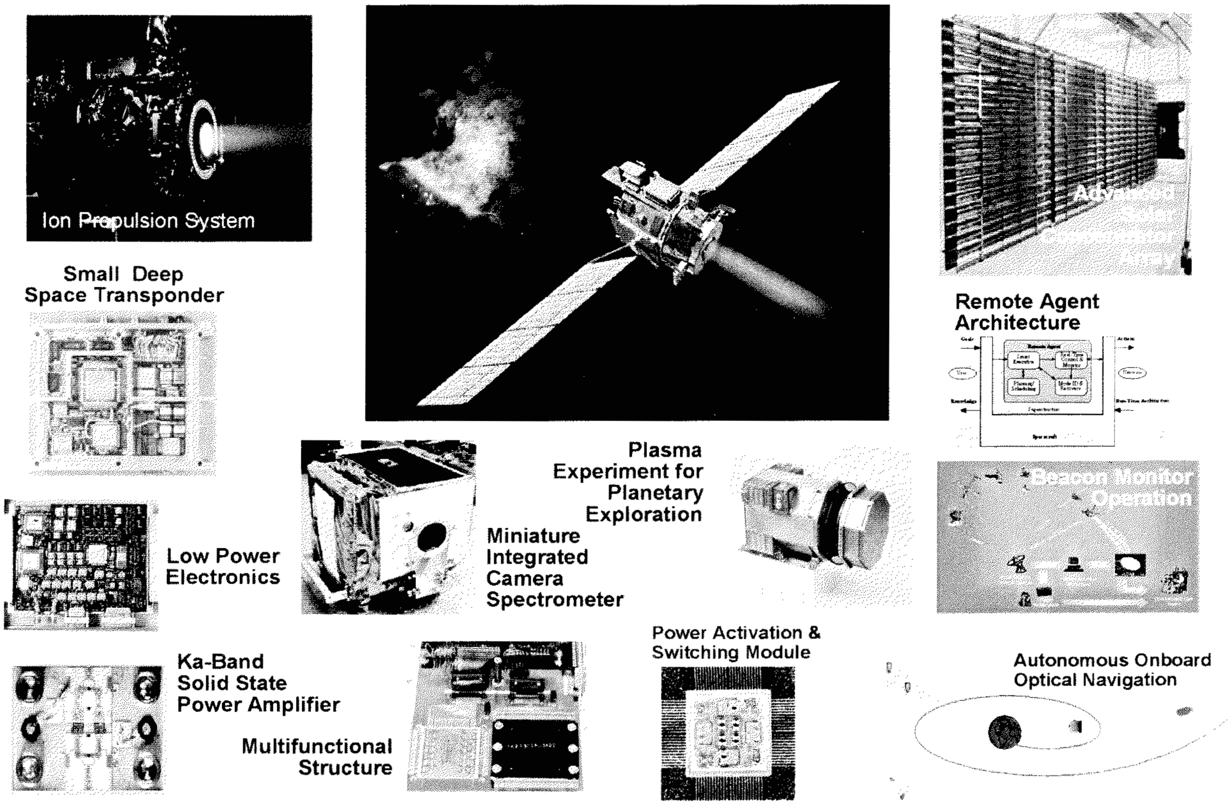


Figure 7. New Millennium Program: Deep Space 1 - Space Flight Validation of 12 Breakthrough Technologies

performance in a realistic system test environment. Interfaces can be either "hardwired" or simulated. The FST customer base has been steadily increasing and now includes about 35 spacecraft projects, instrument development teams, or technology evaluation tasks.

The Project Design Center (PDC) was established in 1994 to support concurrent engineering conceptual design. The PDC facility is primarily used for mission concept definition and for spacecraft instrument design. Users have demonstrated tremendous success in concurrent team design. The PDC facility provides many collaborative tele-design and video communication tools to its users. The facility is fully utilized, serving more than 80 project customers. It also provides an excellent environment for collaboration and teaming with other NASA centers, universities, and industrial partners. Figure 8 illustrates the success of the concurrent engineering teams using this facility.

The Design Hub was established in the latter half of 1997. Its primary function is to support concurrent engineering detailed design for spacecraft and instruments. It is equipped to support a collaborative, team approach to engineering design—not only at JPL but also using tele-engineering with our industrial and university partners. The Design Hub also serves as the focal point of the JPL CAD/CAE tool service and provides a place for CAD/CAE tools classes and symposia. The main Design Hub supports many satellite and virtual design hubs distributed throughout the Lab. The satellite hubs and virtual design hubs are supported by Unix and Windows NT servers as well as computer System Administrators located in the main Design Hub.

Figure 9 schematically illustrates the DNP integrating mechanisms for the design and development process. Key to this integration is the creation of a computer based Product

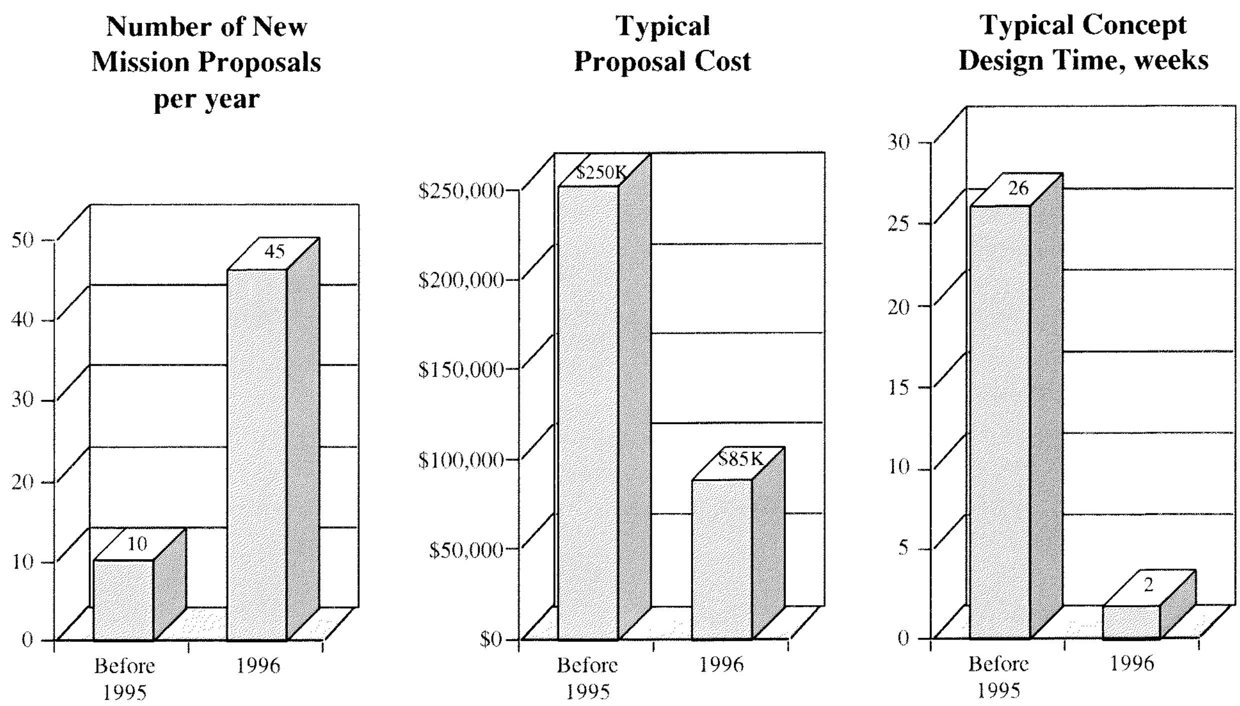


Figure 8. Cost and Schedule Metrics for Conceptual Design

Attribute Database (PAD), which provides on-line, up-to-date design data to team members. Figure 10 illustrates the improvement in communications efficiency achievable through the use of the PAD.

The DNP Project approach is to deliver new capabilities to user projects in phased six-month increments. Early deliveries have been focused on preliminary mission and system design activities. Later deliveries will address detailed design and integration. A complementary development, initiated in 1998, is an advanced multi-mission architecture for an end-to-end information system for deep space missions. The system, named the "Mission Data System,"[4] has several objectives:

- Earlier collaboration of mission, system, and software design,
- Simpler, lower cost design, test, and operation,
- Customer-controlled complexity, and
- Evolvability to *in situ* exploration applications.

The new MDS architecture is based on several concepts:

- Construct subsystems from architectural elements, not the other way around.
- Migrate to the spacecraft (or rover) some of the processing which has traditionally been performed on the ground.
- Make use of models.
- Design for real-time reaction to changes, rather then open-loop or earth-in-the-loop control.

Many of the concepts used in MDS—closed-loop control, onboard resource management, model-based diagnosis—were validated during the Deep Space 1 mission.

A major challenge for the future will be the integration of JPL processes and tools with those of our partners. Even the seemingly straightforward sharing of databases can be complicated by information system security measures, for example.

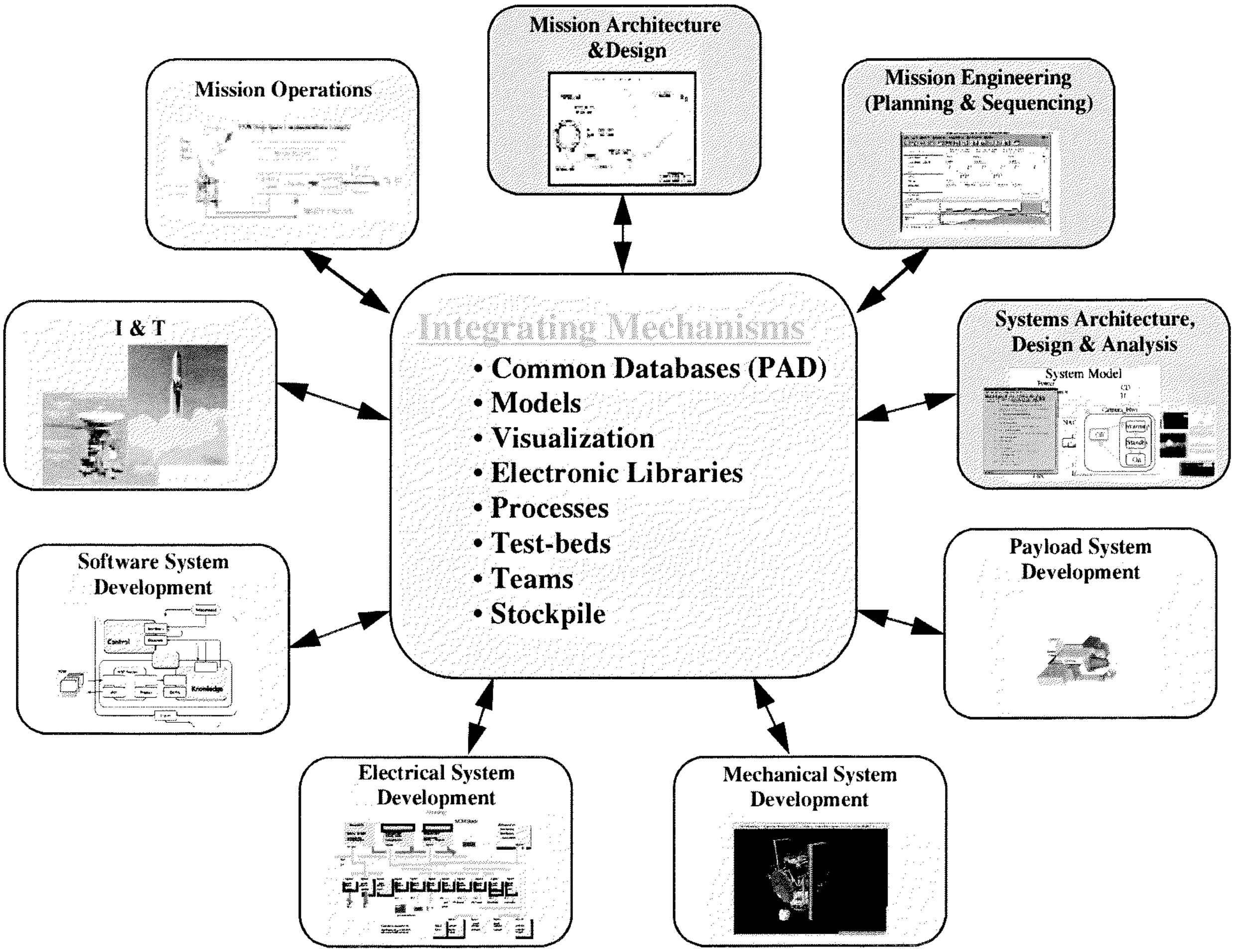


Figure 9. Engineering Process Integration

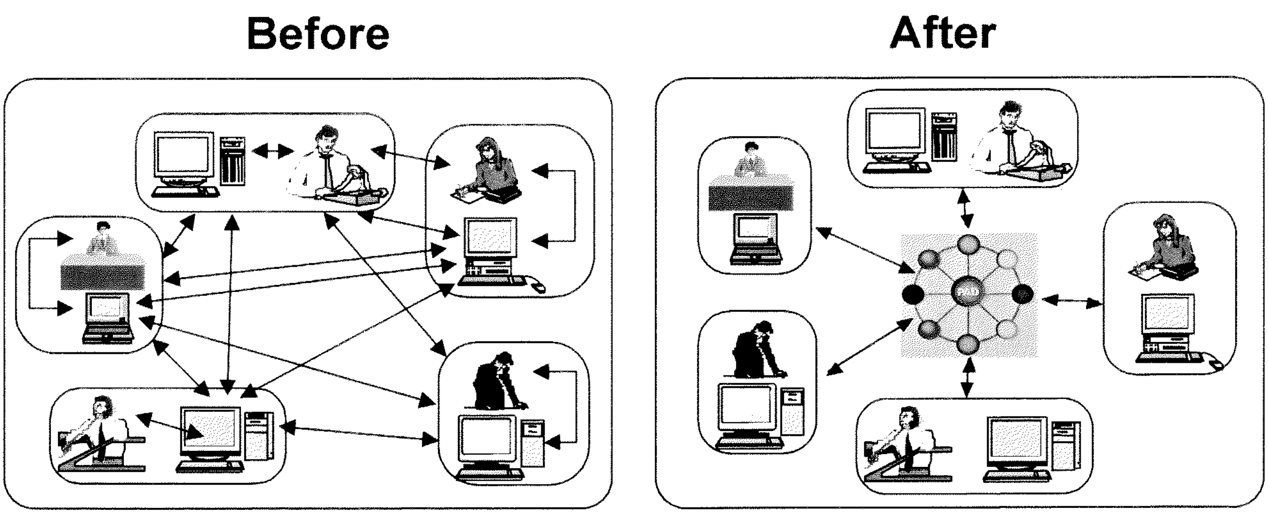


Figure 10. Enabling Technical Communications with a Product Attribute Database (PAD)

A Supportive Work Environment

The success of FBC missions—or indeed of any human enterprise—ultimately rests on the shoulders of the individuals doing the work. In recognition of its own needs in this regard, JPL has adopted an employee goal that states:

We will, as a collective responsibility of all at JPL, create a work environment based on mutual trust and respect that enables high-quality work and promotes personal development.

This goal acknowledges a two-way responsibility. The individual is responsible for accomplishing the work of the Laboratory, and the Laboratory is responsible for providing an environment in which the individual can get his or her work done and grow in the process. This is without doubt the greatest corporate challenge of the FBC era.

Support for getting the work done includes, of course, the efforts described earlier, and it demands wise decisions on institutional investments and allocation of resources. JPL has also installed a new financial management system, reengineered its rule making process, invested in new computer tools and a high-speed local area network, and addressed key staff deployment and sharing issues. The Laboratory is making a transition to process-based management addressing the need for efficient end-to-end work processes focused on the customer, whether internal or external. A facilities council deals with facility allocation issues, such as the need for project collocation.

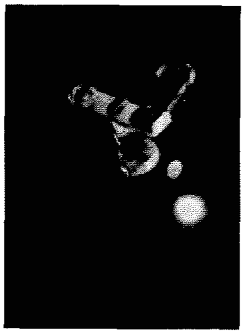
A number of initiatives have been undertaken in attending to employee concerns. An upward feedback process provides employees with a safe and constructive way to improve employee/manager interactions. The compensation system has been redesigned to be market based, and the reward and recognition program has been expanded. A training goal has been established, and progress is being monitored. Project "blackout periods" have been established, centered around major holidays and popular vacation times, to provide guilt-free opportunities for project teams to take time away from the job. A broad based "employer of choice" initiative is addressing a range of quality of life and professional growth goals. Nevertheless, much remains to be done in this area.

Partnership

So far we have addressed the challenges of FBC as if they were internal to JPL. Many are, of course, but the Laboratory subcontracts over half its budget and the need for and frequency of interagency and international partnerships is increasing. Such partnerships are essential to "getting it all done." Figures 11 and 12 give some sense of the major contributions of industrial, governmental and academic partners in contributing to the success of FBC missions. Figure 13 is a partial listing of international collaborations in the FBC era. JPL conducts an increasing proportion of its missions in a collaborative manner. Many of these collaborations are formal arrangements with industry. The upper portion of Table 3 lists companies with whom a collaborative contractual relationship has recently been formed. Personnel from JPL and these contractors function as an integrated product team in delivering essential products and services. JPL also has formal agreements with other government agencies and with universities for specific areas of research, as listed in the lower portion of Table 3.

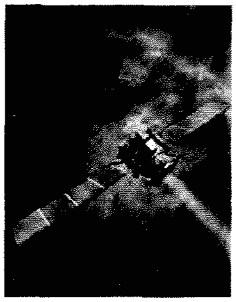
CONCLUDING REMARKS: Leaving a Legacy

In the previous era of deep space exploration, flagship planetary projects left a legacy of technologies, facilities, tools, processes, and experienced personnel almost as a byproduct of their existence. As discussed above, much of this continuing accumulation of enabling capabilities has now been moved outside the fast moving flight projects. The structures and procedures that were tuned to the needs of self-contained projects are being retuned to deal with

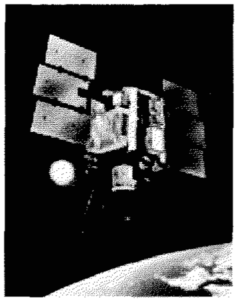


SIM
- Lockheed Martin Sunnyvale
- TRW

Genesis
- Caltech
- Lockheed Martin

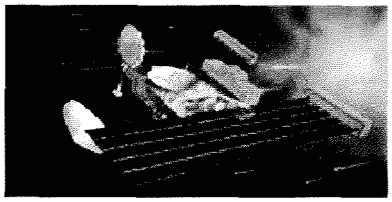


Deep Space 1
- Spectrum Astro
- Ballistic Missile Defense Organization
- Ames Research Center
- Glenn Research Center

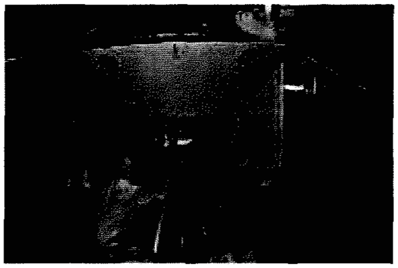


QuikSCAT
- Ball Aerospace
- Goddard Space Flight Center

SIRTF
- Ball Aerospace
- Lockheed Martin Sunnyvale



Stardust
- University of Washington
- Lockheed Martin Denver



Mars 98
- Lockheed Martin Denver

Figure 11. Industry/Academic Partners

Table 3. Strategic Partnering

ORGANIZATION	SCOPE
Raytheon STX	Science Data Operations
Swales Aerospace	Thermal and Structural Analysis, Optical System Design
Composite Optics, Inc.	Composite Materials Structure Design and Fabrication
Ball Aerospace	Flight Instrument and Subsystems
National Reconnaissance Office	Radar Technology and Systems
Air Force Research Laboratory	Optical Communications, Micropropulsion
University of Arizona	Gamma Ray Spectrometry

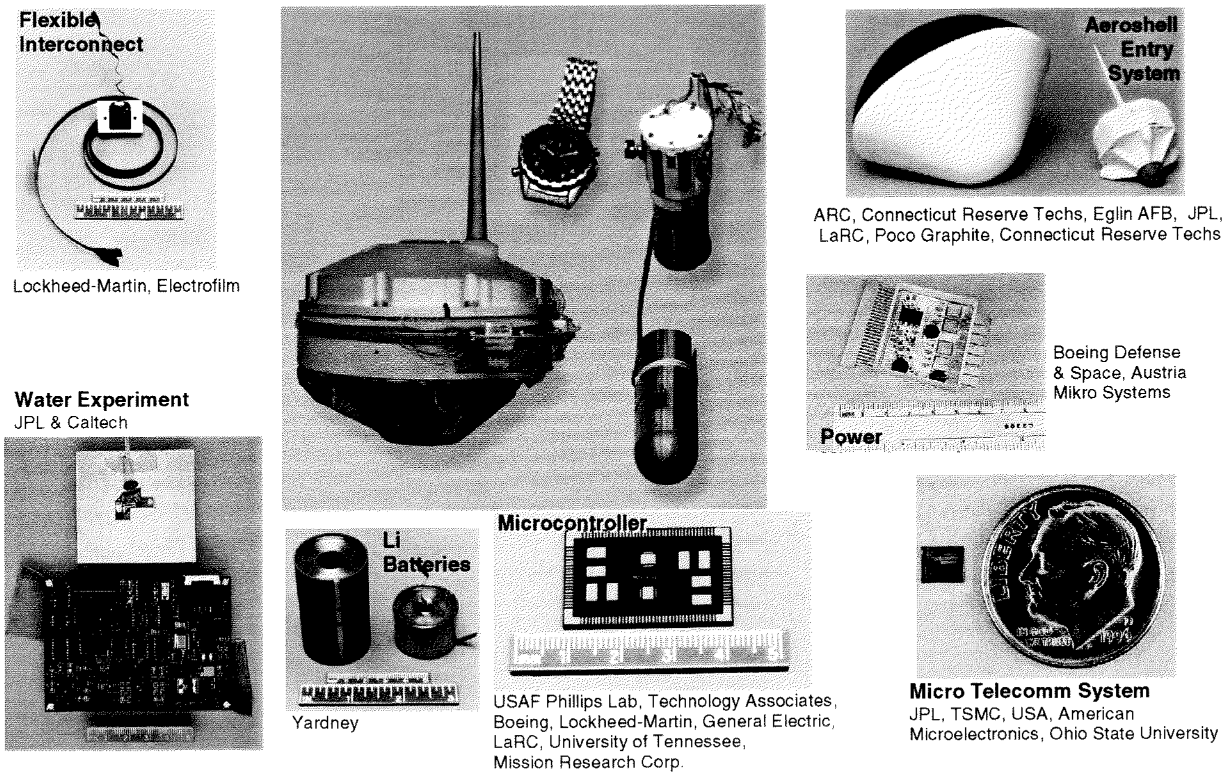


Figure 12. Deep Space 2: Technologies and Partners

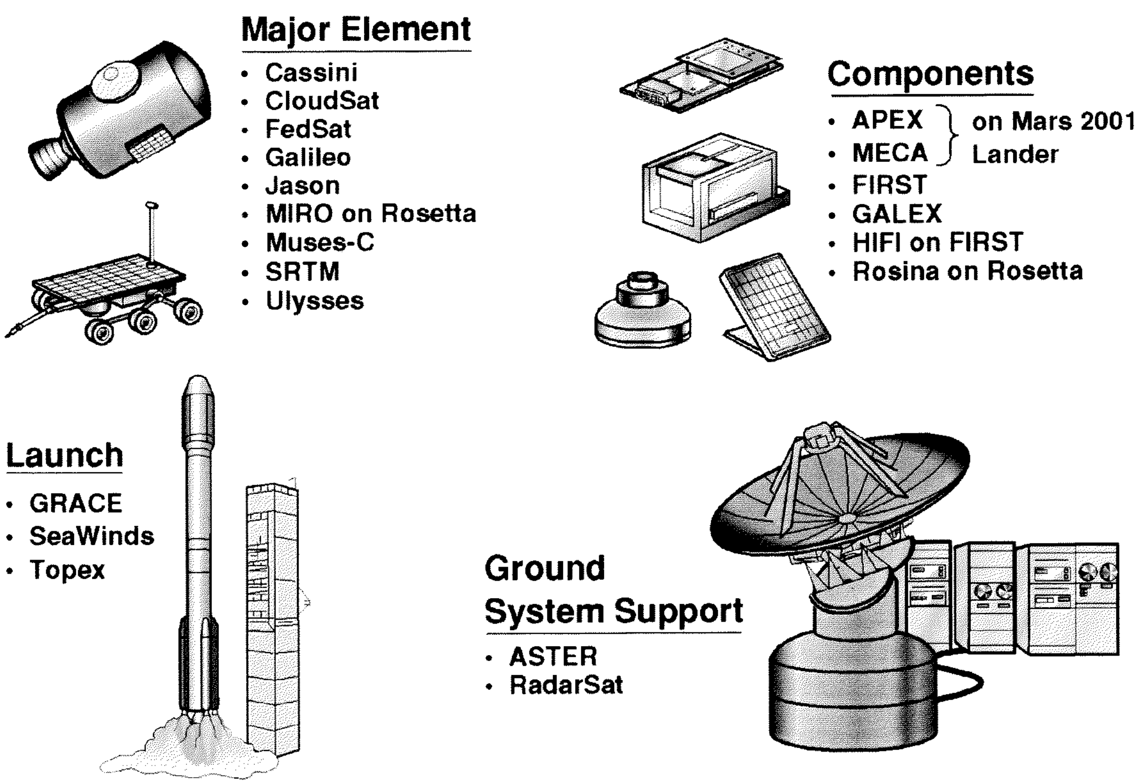


Figure 13. Types of International Collaborations

the issues of sharing resources among current projects and leaving a legacy for the projects to come.

One clear lesson in the faster-better-cheaper era has been the robustness of the program architecture. With programs now designed as an ongoing series of small missions, an occasional failure can be accommodated without destroying the long term viability of the program. Later missions are able to build upon the technology and experience of earlier missions.

The program architecture also creates a continuing source of tension: individuals contribute to an existing mission, but also have an affiliation with a larger set of missions, objectives, and organizations. The new era demands new attitudes and new allegiances. Interdependence must not only be tolerated but cultivated, with a trusting expectation that one's partners will deliver on their end of the bargain.

We are still in the early stages of implementing FBC missions. The long term success of FBC will depend on a willingness by the participants to accept accountability not just to their current demanding and stressful task, but also to their part in the success of the enterprise as a whole.

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