Final

STARDUST: Implementing a New Manage-To-Budget Paradigm

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Abstract—STARDUST is the Discovery Program's fourth mission, selected from a field of 28 original proposals. In the Discovery series, it follows Lunar Prospector, Mars Pathfinder and the Near Earth Asteroid Rendezvous (NEAR) mission. Five years after launch in February 1999, the STARDUST flight system will collect comet samples during a 6 km/s flyby of Comet Wild 2 on New Year's day, 2004, and return the samples to Earth in January 2006. Enroute to the comet, STARDUST will also attempt to collect samples of interstellar dust. Professor Don Brownlee from the University of Washington is the project's Principal Investigator.

The Jet Propulsion Laboratory (JPL) is providing project and mission management with Lockheed Martin Astronautics (LMA) as the industrial partner for the flight and ground systems. LMA is making use of developments in the Mars Global Surveyor (MGS) and the Mars Surveyor '98 projects preceding STARDUST. Under the stringent cost-caps of the Discovery Program, efficient management techniques are mandatory to control costs at acceptable risk levels.

The STARDUST management team is aggressively working to achieve this control through the use of Total Quality Management (TQM) and Reengineering principles, and commercially available software tools. The approach has been to develop project-to-project interfaces to exploit parts stores and common procurements, shared staffing and shared facilities. Inheriting parts, hardware, software and designs is required to leverage dollars and get efficient in doing missions faster and better, while staying inside a constrained budget. Additionally, to achieve the required level of time efficiency and budget control, a new level of communications and data handling (read excellent Management Information System [MIS]) is mandatory. Finessing the rigidity of traditional Performance Management (or Measurement) Systems (PMS) and institutional/corporate cultures requires a new way thinking and a cheerleader aggressiveness. STARDUST has organized toward the Integrated Product Development Team (IPDT) concept as a central feature. This has been matrixed into the formation of a dedicated Product Development Office (PDO) at LMA. The PDO serves the leveraging goal by serving two projects, STARDUST and Mars Surveyor '98. It avoids duplicate project-unique personnel structures and offers cost benefits to each project.

This paper will provide details and example metrics characterizing the aggressive application of the *design-to-cost* paradigm and innovative implementation by the STARDUST management team to achieve success under the Discovery Program budget constraints.

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1. INTRODUCTION

The Discovery Program reflects a new way to continue the legacy of the Mariners, Voyager, Magellan, and Galileo in deep space exploration. Discovery is changing the way NASA does business. It is a central element in a *complete culture change* for planetary exploration and space science. Discovery's goal is to achieve results *faster, better,* and *cheaper.* It will be more effective, do more with less—specifically, carry out planetary flight missions with highly-constrained total cost.

STARDUST was selected from a pool of 28 proposals in 1994. It becomes the fourth mission in the series, preceded by: Near Earth Asteroid Rendezvous, Mars Pathfinder, and Lunar Prospector.

Historically, planetary missions evolved to large, complex platforms with up to 14 scientific experiments and price-tags of up to $2 billion. These missions endeavored to do remote-sensing and in-situ investigations on extremely stringent diets of power, mass, and volume. The struggles in the scientific community to be one of their cramped passengers were difficult and frustrating. With their high price-tags, such missions are clearly on the path toward extinction.

STARDUST is in the process of *reversing* the paradigm. It is a *sample return* mission whose fundamental premise is to bring the essence of the solar system, material from a comet, home! With samples back on Earth, literally *hundreds* of experimenters can participate in analyzing the thousands of particles returned to Earth. They can apply existing instruments—with relatively unlimited power, mass, and volume constraints—which are operational in the finest labs and universities. This will allow participation in solar-system exploration by a broad community. And the opportunity is offered at a Discovery price, less than 10 % of the traditional approach!

STARDUST is the *first* program approved for return of material from a solar-system body since the Apollo and Luna sample-return missions of the 1970s and, more importantly, the *first ever* program for return of material from a comet. As such, it becomes a model for planning follow-on sample-return missions to other planetary bodies. The simplicity and compactness of the Sample Return Capsule (SRC) should be very attractive to follow-on applications. Figure 1 shows the STARDUST spacecraft in its sampling configuration.

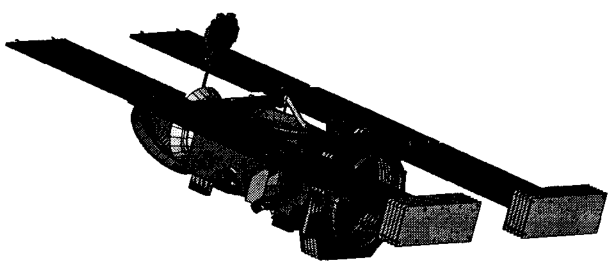


Figure 1. STARDUST Spacecraft

The major features of the STARDUST flight system are: the Sample Return Capsule (SRC), about a meter in diameter, shown open like a clamshell at the rear of the spacecraft, with the dust-collector grid deployed into the dust stream above the spacecraft; the Whipple shields, consisting of two plates with Nexel™ curtains between to stop the high-speed particles from impacting sensitive spacecraft elements, shown at the front of the spacecraft and solar-arrays; solar-arrays, shown along each side of the spacecraft; and the Cometary and Interstellar Dust Analyzer (CIDA), to be provided by Germany. The flight system also carries an upgraded Voyager camera to provide optical navigation capability. The plan is to also use this camera for imaging the nucleus of the comet to a resolution an order-of-magnitude better than *Giotto* imaged *Halley*.

The STARDUST team comprises generally: the Principal Investigator (PI), Dr. Don Brownlee of the University of Washington (UW) in Seattle; the Jet Propulsion Laboratory (JPL) in Pasadena, which manages the project; and Lockheed Martin Astronautics (LMA) in Denver, which provides the STARDUST spacecraft. Instruments are provided by JPL, the University of Chicago, and the Max Planck Institute in Germany. Scientific testing takes place at several other NASA centers. Personnel at each institution collectively form the STARDUST development team.

2. Continuous Process Improvement and Re-Engineering Principles

To operate within NASA's better, faster, cheaper paradigm, and to meet Discovery Program requirements, the STARDUST team was challenged to achieve a very efficient program. Meeting this challenge entailed implementation of many new ways of doing business, which required a combined approach of adopting, changing, and inventing business processes. The paramount goal was, and continues to be, the implementation of *best business practices* throughout the project. How would this goal be met with a distributed team ?

3. Virtual Co-Location: How It Works

Doing business *globally* is becoming a necessity in today's business environment. The JPL teams in Pasadena must be functionally intertwined with the LMA teams a thousand miles away in Denver. With the new role of the PI being in charge, it is essential for the PI, who resides in Seattle, to be able to fulfill his role on a very frequent basis from a location removed from JPL and LMA. Co-Investigator (Co-I) team members located around the country and in Germany must interact often with the other teams.

Through the use of commercially available software tools, and some not-so-commercially-available software tools, the team was linked via an Information and Communications System (ICS) detailed below. The ICS facilitates easy access and frequent communications among all team members, which has significantly contributed to the success of the project as a whole.

A primary benefit of the ICS is to enable the distributed team members to work together and share information as if separated by an office down the hall rather than a thousand miles away. The structure promotes team cohesiveness and open communications—there are no secrets across institution boundaries. Project budgets were defined and worked as one integrated team, and not as a customer-contractor relationship. This relationship proved very beneficial when initial baseline budget plans exceeded a funds available profile. A solution was jointly worked by the teams, and not merely thrown over the fence to the other party.

A second benefit of the ICS is savings on travel costs. In addition to the dollars spent, there is a substantial lost effective time factor, and additional stress on personnel in being away from home. STARDUST, as a matter of course, conducts its Monthly Management Reviews (MMRs) and other recurring reviews co-located "virtually", with no personnel travel required.

Software Tools

A critical decision made early in the program was to decide upon a set of multi-platform commercial, off-the-shelf (COTS) software tools which would be uniformly used by all project personnel, regardless of location or affiliation, for the duration of the program. Prior experience had repeatedly shown that purported software translators never quite did the job 100 % of the time. Moreover, a requirement of translation prior to using the information stored in the files would inhibit communication among the team members—an unwanted result.

While word processing, spreadsheet and presentation software easily defaulted to Microsoft Office™ for various reasons including cost, availability, and ease of use, decisions affecting the program-control aspects of the project were more complex. LMA Flight Systems, on previous and other concurrent programs, used Microsoft Project™ for network scheduling, Microframe Program Manager™ for financial data processing, including earned-value, and FastTrack™ scheduler for presentation-quality top-level schedules. The similarity of these programs and the availability of data made the decision to use the same software tools the logical choice, regardless of the potential superiority of other software products.

While Microsoft Project was one of the more popular network schedulers of JPL personnel, it was not the only product used. The advantage of using the same software as LMA far outweighed the advantages of any other project-planning application. The use of Microframe Program Manager for earned-value planning was another, more difficult problem. JPL, as an institution, does not support any commercial earned-value software product as the earned-value process had never previously been required by a sponsor. However, by fortuity, the STARDUST business manager had previously applied Microframe Program Manager to another project. Thus, the conclusion of using LMA's institutional-standard program-control software was a relatively simple solution. The team at JPL also adapted FastTrack as its high-level scheduler for convenience and continuity with LMA's company practice.

It is noteworthy that starting from a process framework did not drive the team to have COTS software entirely meet intended requirements. Rather, adjustments were made to the ideal processes to accommodate the functionality of the commercially available software, and adaptations were made as necessary to make the process whole, thereby meeting the *best business practices* goal.

File and Server Design

At the center of virtual co-location is one or more file servers. The STARDUST file servers hold an electronic library of all documents produced during the life of the project. A carefully planned structure of the file folders on the server is essential to ease of use, and subsequent retrieval of information residing on the server. After much negotiation, the first-level folders align along functional and WBS lines. For example, top-level folders exist for Business Management; Reviews, Project Engineering and Integration Team (PEIT), and NASA HQ. In general, all folders are fully accessible by project team members to facilitate flow of information between personnel. To maintain some confidentiality of information, certain folders are provided to allow access to members external to the project, e.g. NASA Headquarters, Outreach affiliates, and foreign scientists. Figure 2 presents a view of the STARDUST server directory-folders.

The STARDUST servers are configured to provide local access at both JPL in Pasadena and at LMA in Denver. Every 30 minutes, the servers mirror locally-generated information to the server at the remote location via a dedicated T1 line. The purpose of this configuration is twofold. File transfer time from the server to a desktop for local users is relatively instantaneous compared to some expected delay over the Internet. In cases where megabytes of information are transferred, this efficiency is essential to the smooth operation of the server and provides incentives for personnel to use the system. A mirrored approach provides each generator of a large amount of information to have a complete set of its information at all times. In the event of a network failure between JPL and LMA, LMA and JPL personnel are not without current information. The local users will have a copy of the remote information most recent before the network failure. The local access server also provides doubleclick file-execution capability. All team members removed from the JPL–LMA mirrored sites may access information via File Transfer Protocol (FTP).

Firewalls and Data Networks

At the beginning of the program, commercially available software did not exist that could provide secured mirroring of information between two remote sites. As of this writing, this type of program is still not commercially available. To compensate, LMA developed its own internal "store" program. It initiates pushing of data to the remote site each half hour, and pulling data from the remote site each half hour, staggered 15 minutes from each push. LMA was required to initiate all communications to and from the outside of its firewall to maintain security for its information networks. This firewall system precluded other solutions, for example, operating Windows NT™ (NT) mirrored-servers over a wide area network (WAN).

An issue in providing server access is the ability to provide multi-platform access to information. The STARDUST project initially faced a situation where the UNIX servers at the local and remote locations ran an Appletalk™-only emulator shell, a "universityware" program. While the Appletalk-only access was sufficient to meet LMA's need, JPL's requirements were for multi-platform access, including Apple™, Windows 3.1™, Windows 95™ and Windows NT workstations. Initial attempts to use Windows directly with the UNIX operating system resulted in many scrambled files and frustration among the users. Going to a 100 % Apple-compatible user-set was not an option at JPL.

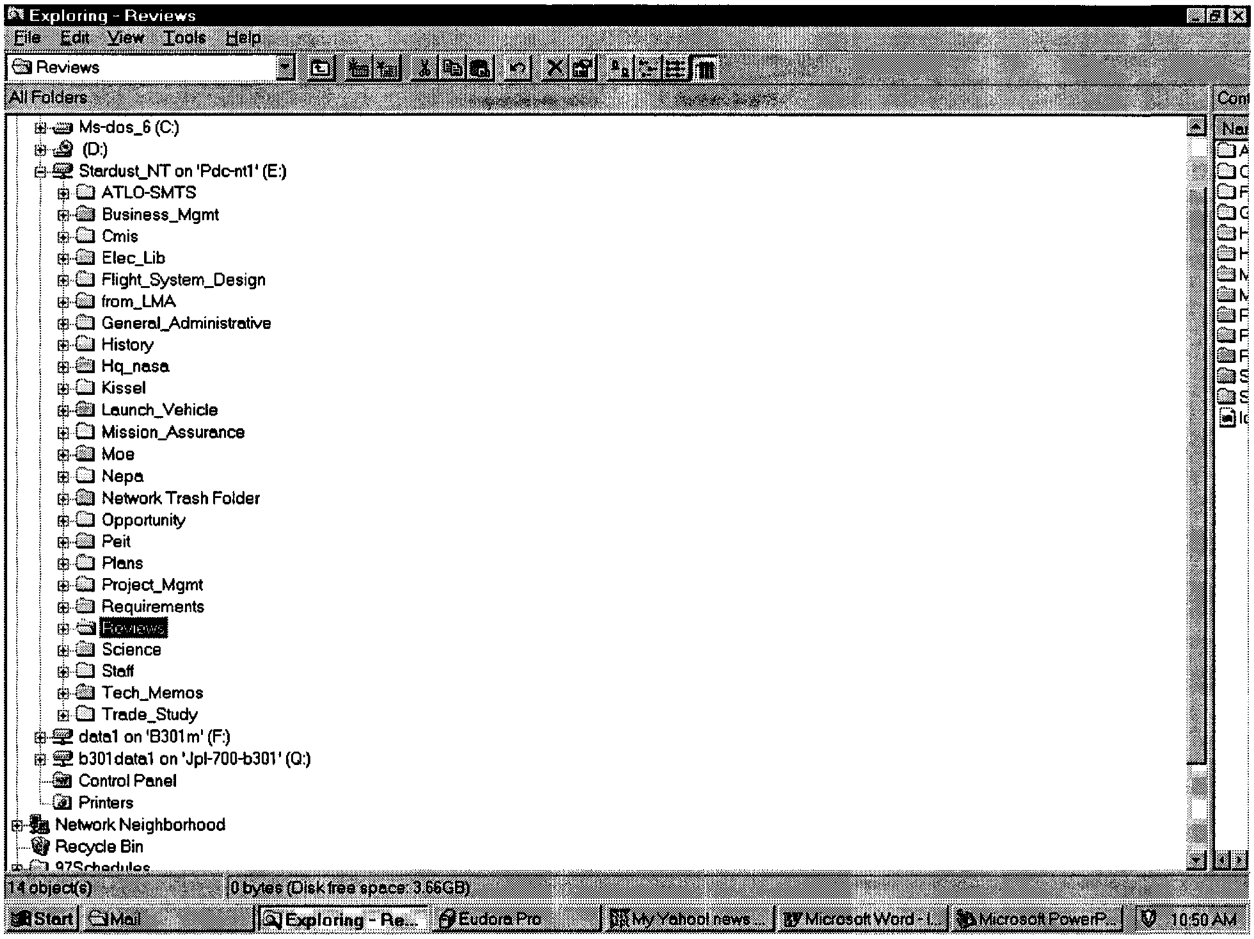


Figure 2. STARDUST Mirrored Server Directory Structure

To solve this problem, a Windows NT server was placed in series with the UNIX server at JPL. The NT server communicated with the UNIX machine via Appletalk-emulators on both ends, which resulted in high-quality data being available to all platforms from the NT. But this arrangement caused additional problems. Because an automatic read/write of files to the NT from the UNIX machine was not possible within the operating systems, the ICS manager was required to manually push and pull information to/from the UNIX from the NT at least once a day. This operation lasted about 18 months. Local users were happy with high-quality information, but the practice resulted in additional workload for the ICS manager, and the arrangement was certainly not optimal. Recently, commercial software became available which emulates an NT server and which runs on an UNIX platform. LMA and JPL have migrated to this new system.

Your Place or Mine (The Meet-Me Line)

In conjunction with the mirrored servers, the STARDUST project has a dedicated meet me teleconferencing line. It allows up to approximately 33 concurrent calls. The teleconferencing line provides the audio portion of the virtual meetings, while files on the server provide the visual portion of the meeting.

Typically, Microsoft PowerPoint™ slides are prepared prior to a meeting, and the files are shared so each participant has ready access. The conferencing facility at JPL comprises a meeting room with a screen, a computer with video output connected to a ceiling-mounted projector, and a table-top conference phone. Participants in meetings have dialed in from Russia, an airline in flight, and a Hawaiian phone booth. With a laptop computer and a modem, the system is globally accessible for participation *equivalent to being in-situ.*

Early in the project, a decision was made not to invest in videoconferencing facilities for three main reasons. First, the cost of each facility is in the neighborhood of about $50,000, and a minimum of two facilities would have to be installed, at least one at JPL and one at LMA. Second, videoconferencing does not easily provide the flexibility required to operate from many locations world-wide, with each attendee participating on an equal basis. Third, having participated in numerous videoconferences, the value added by "virtually looking" at remote participants during the discussion was determined to be minimal.

Voicemail, E-Mail and Pagers

Key to the success of global communications is the capability to communicate often and with relative ease. In addition to such customarily accepted means as voice and electronic mail, the STARDUST project instituted a system of alphanumeric pagers with nationwide coverage for key personnel. This arrangement facilitates relatively instantaneous access for questions, etc., having the "pagee" dial into the meet-me teleconferencing line.

4. Implementing Change—Culture Clash

For many years numerous aerospace companies and JPL operated under the Apollo paradigm; that is, design and schedule generally were concerns paramount to cost. As a result, tools were not developed and used in tracking cost at JPL to the extent that a for profit company would. For cost-account holders, penalties were severe for over-running planned cost, and near heroism was bestowed for under-running cost plans. Thus, a mindset developed (for self preservation's sake) to intentionally budget such that it was highly unlikely that a cost overrun would occur. A further mindset developed in which budgets were considered grant-like, and recipients would hoard them, whether likely to spend them or not. Budget not spent in one year was insisted to be rolled-over into the next, rather than be recaptured in reserves. These conditions resulted in fantasy budgets which, in many cases could not be related to real people and real tasks.

Given these operating conditions, it is likely that the program-control teams had great difficulty in planning for contingencies or understanding what reserves actually existed, because so much money was typically hidden in the planned budgets. Thus, projects operated under smaller fiscal reserves than necessary, and certain decisions regarding expenditures on risk-reduction items could not be intelligently made.

In tracking planned cost and actual cost only, without the integration of schedule, it was difficult to tell whether planned work in fact had been accomplished or whether it was merely deferred. Thus, during a budget revision, it was more likely that replanned prospective budgets would rise without prior warning. The real problem was that there was no *clear* correlation between work planned and work accomplished or between work accomplished and actual cost.

Others had implemented earned-value programs with limited success. Existing earned-value cultures included those who left the room at the mention of earned-value and those who staunchly advocated tri-service-certified methodologies. Our challenge was an opportunity to gain the benefits of having performance-measurement information to facilitate management of the program in a cost-capped environment, without enduring the distress and cost of adhering to the strict discipline of most traditional performance-measurement systems.

Our *tailored* approach has enough discipline to maintain baseline and data integrity without the unnecessary restrictions typical of a tri-service–validated system. The approach was successfully tested during Phase B, and fully implemented at the start of Phase C/D development. As we approach the start of ATLO, the PMS data thus far has proven to be a valuable indicator of true performance against baseline plans. Operationally, all significant variances are initially investigated by the program-control team, and then are addressed by the cost-account owners as necessary to explain the variations. This *tailored* approach to earned-value implementation has helped enable the cultural change toward accepting PMS data as a legitimate tool to help manage the program.

Integrating the Work Breakdown Structure

One of the unique features of STARDUST's Work Breakdown Structure (WBS) is that it is fully integrated between JPL and LMA. That is, there are no overlapping WBS elements between the two enterprises, and they fit together as an integrated whole. Such a structure benefits the project in a number of ways. From an organization standpoint, the team members located remotely from each other are seen as part of a whole, rather than segregated by a particular affiliation or ID badge.

From a program-control viewpoint, there are numerous advantages to a unified WBS. Budgets and cost-accounts are uniformly identified at the same level of the WBS, regardless of the origin of the work. Schedules associated with each WBS element are uniformly identified by the WBS. Project documents, regardless of origin, are uniformly identified with a WBS from whence it came. And, at the end of the cost-accounting period, earned-value can be rolled-up within the WBS structure without concern for misidentification of costs incurred.

Schedules

Detail vs. Intermediate or Top Level—A Communication Challenge—A challenge in the maintenance of multi-level schedules is to insure that the information is internally consistent among the schedules, and that effort is not duplicated in maintaining the schedules. The desired result is that the master information is contained in a single location, and other compilations of the schedule information are derivative, rather than duplicative.

Network-schedule software such as Microsoft Project, while capable of showing rollup information, is not geared toward the display of Level 1 (project level) information in a clean fashion. As described above, a natural selection was FastTrack Scheduler, already used by LMA institutionally to fulfill this need. While FastTrack provides additional flexibility not inherent in MS Project, it does require manual input. A more optimum solution has not been found to date.

With MS Project, intermediate-schedules derived from detailed networks can be created by dynamically linking desired information from the detailed schedules into a separate schedule file. The information in the intermediate-schedule file is then automatically updated when the detailed schedule information is updated, and thus internal consistency is automatically maintained. But this method has a serious drawback which impedes dissemination of the information. The dynamic linking process includes specific file directory information. This aspect prevents the transport of files from one directory to another without breaking the dynamic link, which requires manual input to repair. The virtual co-location aspect of STARDUST requires that the files be easily transferred within and without each institution, thus the dynamic linking of the files is not a workable answer.

A solution to the problem of maintaining intermediate-schedules is found by using the multi-project capability of MS Project. Information desired to be displayed in an intermediate-schedule is tagged in a common-text field of the detailed schedules. All detailed schedules may then be simultaneously loaded into MS Project, and all tagged tasks from the detailed schedules may be selected for display. In this manner, a one time only effort must be invested to identify desired tasks. The information is fully transportable by file name and independent of directory name.

Network Schedules—Critical-paths—While MS Project is probably not the most flexible scheduling tool on the market today, it is relatively easy to use and operates equivalently on Windows and Apple computer platforms. A serious limitation in the product itself is its cumbersome and limited ability to link a task in one network to another task in a second network. These links are critical when numerous products are being fabricated in shops by personnel not necessarily under the control of the end-product holder. The key to the success of any networked schedule is the accurate modeling and control of hand-off points between task/ budget owners.

A semi-manual approach was developed to identify and constrain the known links (or hand-off points) within the separate network files. This approach included duplicating the hand-off points within the delivering and receiving networks. For example, when a delivery is agreed upon by both sides of an interface, it appears in the delivering network as "Deliver XYZ Box to ALTO 68320." It also appears in the receiving network as "Receive XYZ Box from 64400." In the delivering network, it is constrained as a "Finish No Later Than" activity type, and as a "Start No Earlier Than" activity type in the receiving network. These activities are also indicated as receivables or deliverables in a text field, and can be sorted on to provide additional management attention, if necessary. Managing interfaces this way is a bit cumbersome, but it has proven effective. An advantage of identifying and constraining activities in this manner is that it provides early indications (via critical-path networking) when a hand-off point is in jeopardy, as if all of the individual networks were contained in a single database.

Receivables/Deliverables—The Internet A further problem presented itself for the deliveries between JPL and LMA. How would the need dates be tracked against the planned delivery dates ? How is this gap bridged?

A solution to the problem of cross-organizational links is the JPL Customer-oriented Management Information System (CMIS), which was originally developed for the Cassini project. It is a web-based product which provides secure access globally via password control. In its general operation CMIS provides an electronic hand-shake, a date record between the deliverer and the receiver of a product. With its e-mail notification module, deliverers and receivers are reminded of upcoming commitments to one another.

A drawback of the program, however, is the lack of critical-path or schedule-slack information. Program-control team members look to the network schedules for this information. The benefit of this web-based program is clearly the ability of users worldwide to manage their delivery commitments.

Metrics

The STARDUST program-control paradigm was to not to implement a single tool to accomplish all goals—this approach typically results in many compromises which impede implementation of *best business practices*. Rather, the program-control teams developed a *suite* approach that included a number of programs and metrics working together to plan and analyze performance. This *suite* is detailed below.

Event-Driven Performance Assessment Metric (PAM)—The program-control team residing at LMA generates and maintains approximately 30 detailed network schedules. One of the metrics used by the program-control team at JPL to monitor LMA schedule performance is a Performance Assessment Metric, or PAM, which is created from the detailed network schedules. Depending on the length of the task in the network, the PAM assigns a number of events to the task. For tasks of one month or less, start and finish events are assigned. For tasks with more than one month, events are assigned for each month during the task. This method avoids a one-month task being assigned the same weight as a six-month task. The events are then graphed cumulatively over the time-span of the project, and indicate a planned, late-finish, and actual completion of the events. The actual line should fall between the other two, and if the actual line falls at or below the late-finish, the metric indicates that schedule reserve is lost and critical-paths are likely affected. Figure 3 presents a fiscal year-to-date PAM.

Each month, the number of actual events is compared against the plan to yield a schedule-only–driven schedule performance index, which is then compared against the earned-value Schedule Performance Index (SPI) for a cross-check. While the methodology appears to be somewhat arbitrary, it is interesting to note that the resulting schedule performance observed to date with this system has very closely mirrored the performance indices output from the PMS system.

Cumulative Receivables/Deliverables—In a like manner to the PAM metric described above, another schedule trend-tracking mechanism is a cumulative receivables/ deliverables (rec/ del) chart. The rec/ del system is used primarily to track major deliverables internal to JPL and between enterprises, such as Interface Control Documents (ICDs) and JPL-supplied subsystems to the LMA Spacecraft Testing Laboratory (STL) and Assembly, Test and Launch Operations (ATLO). This system tracks the *key* deliverables and receivables. In addition to tracking delivery dates, the system also looks at broken agreements, open or pending requests for agreements, and numbers of schedule slips logged. Figure 4 presents a rec/del near-term snapshot.

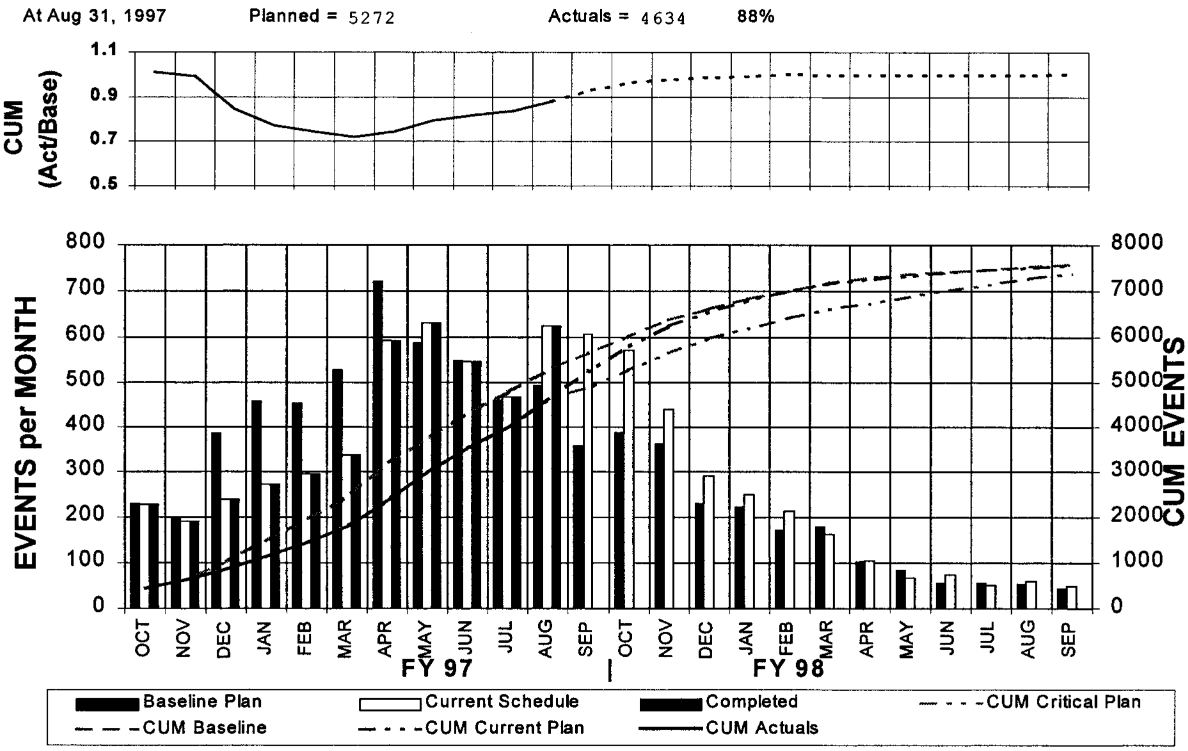


Figure 3. STARDUST Performance Assessment Metric

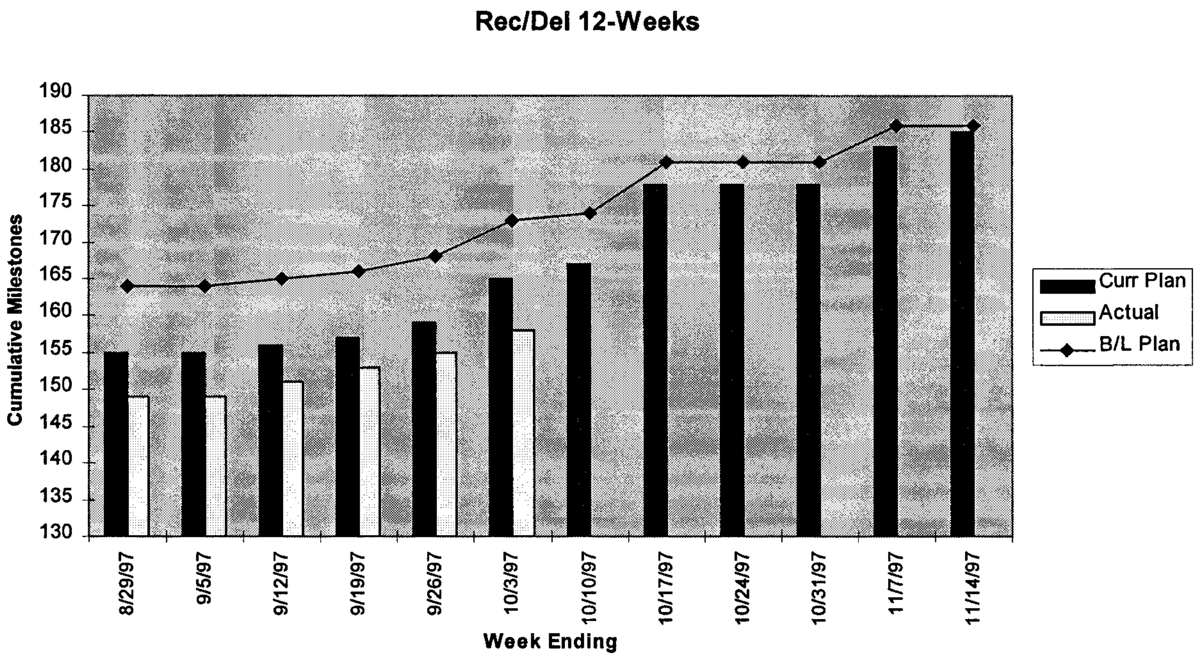


Figure 4. STARDUST Rec/Del Metric

ATLO Days—A key factor in providing a program schedule designed to enable launching on day one of the launch window was the approach taken in the development and management of schedule margin. Emphasis was placed on the lessons learned from recent, similar spacecraft programs. The distribution of margin was influenced by several factors, including the probability of problems and the ability to recover at various phases of the program. Thus, a step function to margin management versus a straight line percentage was implemented. This resulted in allocation of a one-month schedule margin to each subsystem delivery to ATLO.

Table 1 presents a spreadsheet showing the ATLO need date versus the planned delivery date of the subsystem to ATLO. Generally, schedule-slack above 20 days results in a green identifier, between 0 and 20 days a yellow identifier, and 0 or negative a red identifier. This metric quickly and concisely identifies schedule concern areas so appropriate action may be taken.

Table 1. STARDUST ATLO Days Metric

Hardware	Need Date	Available*	Margin
ACS			
Sun Sensors	**02/12/98**	**08/15/97**	**(A)**
IMUs	**⅛8/98**	**11/13/97**	**45**
Star Cameras	**⅛8/98**	**01/05/98**	**17**
Telecom			
CDU/TMU	**01/08/98**	**09/12/97**	**74**
DSTs	**01/08/98**	**10/20/97**	**48**
SSPA	**01/08/98**	**11/03/97**	**38**
Diplexer	**01/08/98**	**04/09/97**	**(A)**
Couplers/Switches	**01/08/98**	**09/15/97**	**73**
Cables	**01/08/98**	**11/06/97**	**35**
HGA (Rx)	**02/12/98**	**06/26/97**	**(A)**
LGA (RX)	**02/12/98**	**12/01/97**	**45**
–Z LGA Tx/Rx	**⅛8/98**	**12/01/97**	**34**
MGA	**02/19/97**	**11/17/97**	**58**
C&DH	**01/06/98**	**01/19/98**	**–9**
EPS			
PCA	**01/06/98**	**12/03/97**	**16**
PIU Assembly	**01/08/98**	**12/08/97**	**15**
SASU	**01/14/98**	**12/17/97**	**12**
Test Battery	**02/20/98**	**02/20/98**	**0**

Earned-value—The earned-value metrics are central to the understanding of the pulse of the program over time, i.e. true performance. In previous programs, a contractor would provide only a NASA form 533 to the customer on a monthly basis, which contained data that was at least a month old by the time it was received. With the common software tools used between JPL and LMA, evaluation of earned-value results were greatly simplified. In accord with the new openness and partnership between the two organizations, LMA provided their internal earned-value information in the form of an electronic file to the program-control team at JPL, usually within one week after earned-value sessions had been completed. The ability of the program-control team to identify potential problems early is thereby greatly enhanced.

By having a copy of the internal LMA earned-value file, the program-control team earned-value analyst was able to perform a very thorough, timely, in-depth analysis of the results at LMA, and directly provide assistance and feedback to the team at LMA. In this manner, the work performed at JPL was beneficial and complementary to the work performed at LMA, by helping focus on the exceptions.

The high worth of the analysis of the LMA earned-value information became obvious within the first few months of Phase C/D, when the personnel ramp-up at LMA did not match the aggressive, earliest-possible schedule that was baselined. It also became apparent that some of the work planned was falling behind more than schedule-slack could tolerate. The ability to perform in-depth analysis of the earned-value information prompted a recovery replan early in the program, and did not allow the problem to languish and grow worse over time. In sum, the integrated earned-value approach of the STARDUST program has proven itself many times to provide substantiated early-warning to problems, thus facilitating timely application of resources to recover. Figure 5 presents a sample earned-value metric.

Financial Risk Management

Managing Cash-Flow—As with many other projects, STARDUST, at its inception, had the dual problem of very little schedule time to launch, and not enough money early on from the sponsor to purchase long-lead items to meet the schedule.

The long lead problem was solved by working with the sponsor to obtain sufficient funds earlier in the program. This early funding preferral allowed STARDUST to both purchase parts in time to meet the schedule, and saved dollars by piggybacking existing procurements from vendors for other programs.

In the spirit of partnership with LMA, the problem of early funding was further alleviated by collectively managing the billing of costs so as to conform with the funds available from the sponsor.

Managing Reserves—When faced with an essentially fixed-price program, effective management of financial and schedule reserves is vital to the survival of the project. The penalty of a cost-overrun of 15 % in today's NASA environment is cancellation. For Discovery Programs the 15 % will not be tolerated; the program starts with an agreement with NASA that the program will be completed for the commitment in the proposal, *and no more*. The result of a schedule stretch-out is a cost overrun, which effectively is cancellation.

JPL

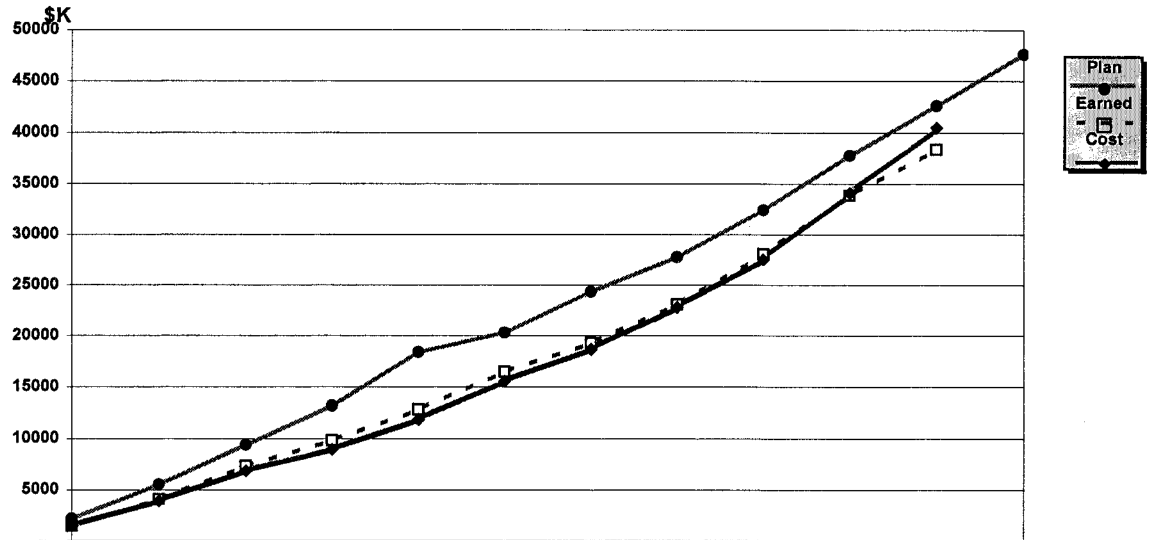
STARDUST

COST PERFORMANCE MEASUREMENT

August 1997

Program Earned Value

FISCAL YEAR '97



		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
C	Plan	2155	5542	9386	13153	18378	20298	24340	27799	32435	37799	42628	47588
U	Earned	1448	4104	7337	9831	12793	16479	19273	23091	28079	33854	38396	
M	Cost	1470	3919	6881	8942	11869	15572	18683	22783	27574	34097	40479	

Schd Var	-707	-1438	-2049	-3322	-5585	-3819	-5067	-4708	-4356	-3945	-4232	
Cost Var	-22	185	456	889	924	907	590	308	505	-243	-2083	
Plan- Act	685	1623	2505	4211	6509	4726	5657	5016	4861	3702	2149	

Figure 5. STARDUST Earned-Value Metric

For missions that are dependent on critical planetary trajectories in order to fit on the small launch vehicles permitted for Discovery missions, schedule slip is not an option.

The implementation of detailed budget plans is central to the understanding of the reserves posture. Detailed planning necessarily stimulates the planner to better understand the nature of the task, which generally results in fewer omissions that need to be covered by reserves at a later time.

After assessment of the general design-maturity of the flight subsystems, many of which were essentially build to print of prior or concurrent programs, the team settled on a 10 % reserves floor guideline based on the program's cost to complete. This floor was intended to provide a declining required-reserves level over time to cover unknown unknowns, and would not be violated except under extreme circumstances. Any sustained move toward the 10 % floor will result in heightened focus on reserves maintenance. Figure 6 presents a percent reserves vs. Cost To Go graph against a 10 % reserves floor.

Encumbrances against the reserves include hard liens, or those that were accepted by the teams and management, and soft liens, which were relatively more uncertain threats anticipated by team members. The total value of the encumbrances of the soft liens are reduced by a factor of probability of occurrence to yield an effective encumbrance against reserves.

A benefit to understanding with relative accuracy the fiscal reserve picture is the ability to periodically release reserves to reduce technical risk while still maintaining adequate reserves to allow for unknown unknowns. During the first year of Phase C/D, STARDUST purchased approximately $900K in risk-reduction items, including additional testing equipment, parts, and spare electronic boards. The additional equipment is intended to be a preemptive strike to avoid contention for test equipment during board and box testing, and against problems which typically occur downstream in the program, usually during ATLO. The additional equipment would facilitate the addition of parallel operations, should they be necessary to recover the schedule.

Unencumbered Reserves vs. Cost To Go

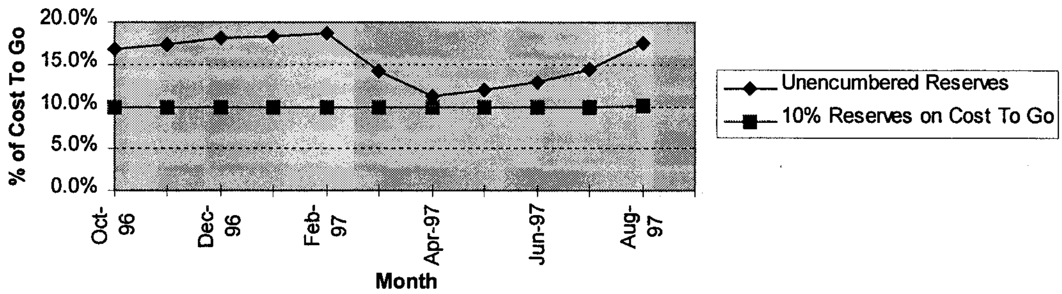


Figure 6. STARDUST Reserves on Cost To Go Metric

5. Lessons Learned

About Understanding Earned-Value Data

The earned-value plan (schedule and budget) can be put together in a variety of different ways, from optimistic to most likely to pessimistic, all of which have legitimate uses. When planning an optimistic schedule, the downside is the probability of falling behind schedule almost immediately. This result must be taken into account when looking at the earned-value results. However, the optimistic approach has a forcing function benefit which is not obtained through the other planning approaches. For the STARDUST project at LMA, the optimistic approach was applied, planning tasks to occur as early as technically possible. This approach was taken in recognition of the importance of meeting a limited planetary launch window and to gain synergy in workforce and procurement activities with the Mars Surveyor '98 program. In many instances STARDUST merely bought another production copy of a Mars Surveyor '98 component rather than starting procurements from scratch. This process allowed STARDUST to gain an economy of scale which otherwise would have cost much more.

The thresholds of the earned-value results for an optimistically planned budget must be looked at in a different light than the earned-value results based on a "most likely" planned budget, because poorer performance against that plan is expected. This approach requires assessing schedule-performance indices together with cost-performance indices and schedule-margin metrics. These three measures together provide clearer information on whether or not poor schedule performance against the baseline is a true problem which must be addressed.

Another planning factor which affects earned-value results are agreed-to scope changes which are not yet reflected in the plan. Clearly, if costs are expended which are not baselined, a serious impact on cost variance is observed. A second result is that schedule variance is likely impacted, because workforce is being applied to unplanned tasks rather than tasks in the baseline plan. Thus, to maintain integrity of the earned-value system, frequent and rapid approval of changes and updates to the baseline plan are required as soon as possible after a decision is made and costs are negotiated.

Yet another result of detailed earned-value planning is the likelihood that the plan itself is of much higher integrity. As was observed in the STARDUST project, detailed planning forces cost-account managers to think in greater detail about the tasks, resulting in fewer omissions. Secondly, detailed planning reduces the possibility that unneeded, "ghost" workforce may be contained in the plan. By observing a naming names approach, only those realistically working on the program pass the test of scrutiny. At the end of the first year of phase C/D, actual expenditures at JPL were within 2 % of the plan.

About Networks

In any schedule-critical program like STARDUST, it is extremely important to be able to assess the impacts of schedule status and changes. This is best accomplished by having program schedules that are produced as a result of relatively detailed and fully integrated critical-path networks. This can be accomplished within a single database or through the use of multiple files. In either case, importance must be placed on defining and controlling the key hand-off, or interface, points. In using multiple files, additional care must be taken to manage potential changes to interface activities on STARDUST. This was accomplished by clearly designating activities within the networks as receivables and deliverables. Dates for these hand-off points were agreed to by both sides and changes were strictly managed. This had the same effect as using targeted dates common in large network databases.

The approach of defining discrete work flows (networking) for scheduled activities coupled with strict management of interface points provided management with a clear and accurate assessment of critical-paths, schedule margin, and schedule risk.

About Cultures

Wresting free of the Apollo mindset and releasing the chains of a customer-contractor relationship are necessary for the STARDUST team to achieve true partnership cooperation. These changes involve not only doing business differently with different tools —they require open communication among distributed team members in a working together fashion to solve problems collectively. The cultures at JPL and LMA (and most other institutions) have for decades resisted such openness because of perceived or real suspicion and reluctance to share information previously labeled proprietary or internal. Internal rules about such sharing have also hindered the transition.

The benefits of such a partnership arrangement are many, however. Team members wearing one type of badge do not duplicate work performed by another—a shadow organization does not exist at JPL. While the sharing LMA detailed earned-value information has allowed program-control scrutiny to a deeper level of detail than traditionally, the analyses performed at JPL have complemented the work performed at LMA and provided an extra hand where needed. Joint solutions were found to solve funding and budget problems discovered early in the program.

About Risk Management

The three major forms of risk in a program such as STARDUST are technical, financial, and schedule. In the Discovery Program all three forms of risk are considered equally important. From a schedule and financial-risk-management standpoint, the lessons learned are that information flow and communications are key to success. A *suite* of software tools and metrics to take the pulse of the program is essential to the making of informed decisions.

A well-known reserves posture is essential to reduce program risk. Reserves become well known when *detailed* budget plans are put in place, and expenditures are tracked on an *earned-value* basis. This practice enables the releasing of reserves periodically *early in the program* to *purchase insurance* against future anticipated risks.

Another benefit of the schedule-reserve plan was the planned phased release of schedule reserves during the program. Of four months total schedule reserves for Phase C/D, planned at the inception of the program, the first month was planned to be phased down for the subsystem deliveries to ATLO. Schedule metrics used by the program-control teams facilitated decisions again on the use of reserves early in the program to repurchase time prior to ATLO start by the use of schedule incentives to vendors or the addition of workforce.

6. Summary and Conclusions

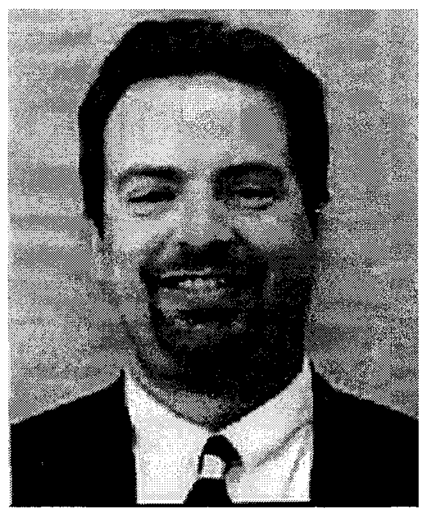
With less than a year to go before launch, the STARDUST program is an icon of the *better, faster, cheaper* paradigm. It has successfully implemented an integrated information- and communication-system infrastructure that virtually co-locates project teams around the country and overseas. A suite of program-control tools and processes brings critical information about project progress to personnel in a clear informative manner. Travel time and expense is reduced over traditional distributed tasks. Nearly one million dollars were allocated from reserves to risk-reduction items during the first year of development as preemptive strikes against future anticipated problems.

In sum, STARDUST has stepped up to the Discovery Program plate and become a model program to be followed in the future.

ACKNOWLEDGEMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, in Pasadena California; Lockheed Martin Astronautics, in Denver, Colorado; and the University of Washington, in Seattle, Washington. The Jet Propulsion Laboratory is under contract with the National Aeronautics and Space Administration to manage the STARDUST project. Lockheed Martin Astronautics is under contract with the Jet Propulsion Laboratory, California Institute of Technology, to provide the STARDUST spacecraft. Dr. Don Brownlee of the University of Washington is the STARDUST project Principal Investigator.

Bredt Martin *joined STARDUST as Manager of Business Operations and Information Systems in January 1996 following its selection as the Discovery 4 mission. He first worked at JPL in 1986 as a thermal environmental engineer in the Mission Assurance division, supporting various projects including the Microwave Limb Sounder for the Upper Atmosphere Research Satellite.*



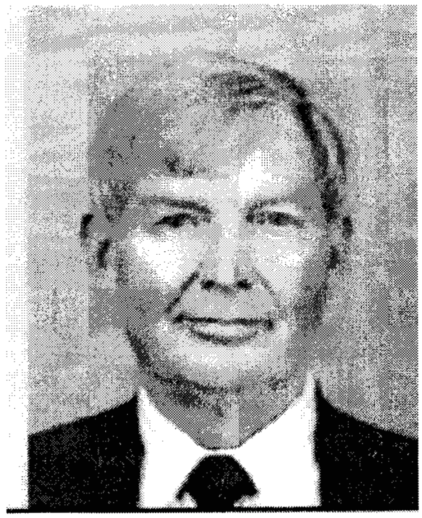
In 1990, he became Planning Manager for the corrective-optics Wide-Field/Planetary Camera (WF/PC) II, which was installed into the Hubble Space Telescope during its First Servicing Mission in 1993. Under the program management and control techniques he developed, WF/PC II was delivered to the NASA customer ahead of schedule and within budget. Later, he was Program Control

Manager for the SeaWinds scatterometer project. There, he co-developed the innovative, low cost earned-value system which is now applied to the STARDUST project. He holds a Bachelor of Science degree in Mechanical Engineering from the University of Washington, and a Master of Business Administration degree in Corporate Finance from the University of Southern California.

***Ken Atkins** joined STARDUST as Project Manager in June 1995 during its Phase A competition for selection as the Discovery 4 mission. He first worked at JPL as a member of the technical staff in propulsion and mission analysis focusing on small body missions, then managed U.S. options on missions to Halley's comet in the late '70s. He next managed the JPL Power Systems Section which, under his leadership, successfully delivered the Galileo power subsystem.*

He later managed the Flight Command and Data Systems section focusing on deliveries of the Cassini command and data subsystem, development of flight software for the low-gain Galileo mission, and flight operations for Voyager, Galileo, and Mars Observer. He also managed the integrated avionics development for the Mars Pathfinder Discovery mission. He has a doctorate in aeronautical and astronautical engineering from the University of Illinois.

***Joe Vellinga** is currently LMA Program Manager for the STARDUST spacecraft and sample return capsule development. He was the proposal manager for the seven spacecraft proposals submitted by LMA in October 1994 for the first Discovery competition and was Program Manager for both the Suess-Urey and STARDUST competitive Phase A studies. He was program manager for the VIRSR seven color imager for the polar orbiting operational weather satellites Phase B study for NASA/GSFC. He also managed the program definition efforts for high resolution imaging spectrometers. He was program manager of the Manned Maneuvering Unit program bringing the flight units out of storage, testing them and preparing plans for re-certification and re-flight. He did the Faint Object Spectrograph system engineering, managed system test and managed the program for integration into the Hubble Space Telescope. He was payload manager for the SCATHA spacecraft, a research satellite carrying over 20 separate payload instruments. He supervised experiment integration compatibility activities for the Skylab corollary experiments.*



Earlier activities included propulsion research and development, bi-propellant reciprocating engine development for lunar power and aerodynamic analyses of supersonic inlet control systems. He has a Bachelor of Science degree from the University of California at Los Angeles.

***Rick Price** joined the STARDUST Flight System team as Chief of Program Planning and Control in April 1996. He has worked at LMA since 1980, beginning with the Titan 34D program. He has served as Chief of Program Planning and Control for the Commercial Titan, Titan II, and Titan IV launch vehicle programs. His experience includes extensive critical path schedule development and analysis, and Cost/Schedule Control System Criteria (C/SCSC) applications in both commercial and DoD environments. Rick was also instrumental in LMA's corporate development and implementation of the Integrated Product Development (IPD) management approach. He has a Bachelor of Science degree in Business Management from California State University Long Beach.*