DEVELOPING A KNOWLEDGE INFRASTRUCTURE TO PREPARE SMALLER TEAMS TO FLY MORE SPACE MISSIONS

Larry Bryant, Ruth Fragoso, Diane Miller, Stephen Licata, John Gilbert
California Institute of Technology/Jet Propulsion Laboratory
Pasadena, CA
and
Jonah Neugass
Northern Arizona University
Flagstaff, AZ

ABSTRACT

Be they flagship or dinghy, space missions must be operated smarter for our space programs to remain viable elements in our national interests, This means putting the cognitive capabilities of fewer individuals to better use. Terms like generalist, multi-tasking, cross-training, and systems guru come to mind in this context. The value of systems knowledge and cross-training was proven in meeting Magellan's challenges. Cassini is currently capturing the system and subsystem knowledge gained during development and test activities. Galileo has put in place a knowledge tool addressing their Phase II Software developed for their lower data rate mission. Information will be accessible in levels of detail to prepare individuals to understand the overall system and quickly locate needed technical details throughout the mission. These efforts will provide a scaleable template which can be adapted by other projects to aid them in developing lean but robust flight teams

OUR STARTING POINT

By moving into a New Millennium of Space Exploration, we have taken on a new challenge in operations. This challenge has even spilled backwards into the flagship era of Cassini. The challenge is developing the capability for fewer people to fly the big spacecraft and for a single small crew to fly multiple small spacecraft.

It is not just a matter of reducing staffing since this translates into increased risk which is unacceptable. It is a matter of smarter staffing. Because operaters will be required to deal with more subsystems, their knowledge base must be broader and their readily available resources must be deeper. They may remain specialists in one area, but they will also need to add a generalist dimension to their capabilities. Traditional operations training has focused on the functionality and behavior of the system. The how of the system function was more important than the why.[1] A new approach or emphasis in preparing individuals to conduct operations is called for. Specifically, a new approach to providing the information needed to safely operate a spacecraft and deal with the problems that are certain to arise in flight. Not only the how must be learned, but the why must be immediately available bemuse. much more of the problem analysis will fall 10 a great many fewer operators.

THE MAGELLAN LESSON

One might reasonably ask, what a generalist buys you. For Magellan, it was survival. Magellan weathered the mysterious "walk-abouts" as well as surviving the budget rrx with its cross-trained "1 .ean Mean Gravity Team".

As (sub)system sophistication grows, having in-depth expert list available for subsystems no longer ensures hat the project can reliably address and resolve in-flight subsystem failures. The Magellan "walk-abouts" are a case in point. in addition, with in-flight spacecraft not being right at hand for examination, there has often been a bit of luck involved in the anomaly resolution process. The Magellan experience points up the value of something more--a systems perspective.

During the mapping mission al Venus, Magellan began experiencing unexplained losses of orientation. For some unknown reason, the spacecraft would lose attitude reference and just "wander off-point" for p rolonged periods of time. After countless hours of investigation and analysis by the experts, the Magellan team was just about ready to attribute the experience to random gremlins. Then the failure was replicated while a sequence was running in the ground version of the spacecraft, the Systems Vilification I .aboratory (SVI.)

All of the attitude control and command and data system elements, both hardware and software, appeared to be functioning properly, and individually, they were. What the team discovered was that as the software modules were running, there was a small, but finite time in the logic when a variable was not defined. They also found that every million times or so that the variable was needed by attitude control software, it was called at the time when it was not defined. This was causing the attitude control system to loose touch with reality and go '(walk-about'>.

Without looking at the bigger picture of how and when elements were working together, and without a significant amount of luck in SVI., this propensity of the spacecraft to routinely wander off might never have I'cell corrected.

Such efforts got Magellan through its primary mission, but there was still a desire to do additional gravit y experiments with what turned out to be a very robust spacecraft. On the other hand, the budget pressures dictated that business as usual was not acceptable for this scientific target of opportunity. After a great deal of consideration and consternation, the Magellan team made a bold move.

They undertook to cross-train the subsystem experts and provide them with fundamental knowledge of other subsystems, to broaden their knowledge base and give them a generalist perspective. in this way, it was felt that the staffing could be reduced to a skeleton crew that could still effectively operate the spacecraft, but at significantly reduced personnel costs. The success of this effort is well documented in the '1'earn's citations for NASA Awards and Medals. Magellan was able to break new ground in space exploration during their aerobraking experience with a flight team significantly smaller than any prior team for such a complex and fully functioning spacecraft.

HOW DO WE GROW GENERALISTS?

Back then to our approach for building generalists. Quite clearly, it is not possible for most individuals to absorb detailed information about the design, function, and operation of every subsystem on a large spacecraft like Galileo, *nor* for multiple simpler spacecraft. We learned in a study " with Voyager spacecraft analysts that the best understanding of the spacecraft belonged to the analyst who had a mental map of the spacecraft as a system. He understood the interaction and interdependence of the subsystems that determined whether the spacecraft worked as a spacecraft or as a collection of separate uncoordinated electromechanical devices. This kind of understanding should be a primary objective in developing our approach to cultivating generalists. Clearly, another major objective is easy access to the detailed information which provides the foundation for understanding the system and supports the detailed tasks performed as part of flight operations.

These two objectives lead us to a multi-layer system for educating and supporting our new era generalists. The top layer is an educational tool to provide the necessary understanding of the system, the interdependence of the subsystems, and its operation. The bottom layer is a reference tool for access to design, test, procedural, lessons learned, and anomaly information for each spacecraft subsystem. Any intermediate layers will depend on spacecraft complexity and resource limitations. Described below are two efforts at the Jet Propulsion Laboratory (JPL) undertaken on the Galileo and Cassini projects to put in place systems that can be utilized in preparing generalists for both these flight teams. These tools can also be used as templates for systems scaled to the needs and resources of the smaller projects coming in the New Millennium so the systems can develop and grow along with the projects to further minimize unnecessary effort in collecting information and structuring the educational tool and reference tool.

As we structure and develop our tools we need to keep in mind some fundamental questions: How much should one person be responsible for performing? What level or depth of knowledge should be expected? Who are the right experts in the field from whom to elicit information? How and in what form will information be captured? What resources should exist? Should the person know the information or just know how to access it? The answers to these questions provide guidance in determining the scope of each level, how and when information is collected, and how each level is presented.

CASSINI EDUCATION AND REFERENCE TOOLS

The Cassini mission will extend from 1997 to 2004. Staffing profiles began leanly for a large flight project and are expected to become even leaner. The challenge of multi-tasking flight team members and the risk of losing valuable information throughout such a long mission is a concern. How the spacecraft is designed to operate, operating constraints, and subsystem idiosyncrasies are a few of the important areas recognized where information should be captured, disseminated, and kept current and available throughout the mission. Several options were considered for capturing general and detailed information from the spacecraft developers for use in flight operations. Two parallel efforts were undertaken to both capture the information and to put it into an easily accessible and effective form for information transfer.

The initial capture effort is ongoing and straightforward, using in-house facilities for video taping lectures from subsystem developers. For capturing a specific set of data, this is an effective approach, but it has drawbacks for effective information transfer. Prior to the presentation, an outline is developed based on perceived customer needs and provided to the presenter. The presenter and the core group of engineers who are the "customers" of the tutorial met to discuss the outline and lecture content. The presenter reviews his planned presentation and the customers provide inputs with respect to the subject covered, depth of treatment desired, additional topics, and any other relevant aspects to focus the presentation to customer needs. The presenter then has a better idea of operational concerns and implements the inputs. If additional exchanges are needed they are scheduled, otherwise the presentation takes place. A question and answer session is included either throughout the presentation or at the end to allow for audience participation and clarification of details and areas of uncertainty for the audience. Additional Video taping, during the Spacecraft Assembly Facility (SAF) test and integration phase of Cassini development is presently being scheduled. This will be an opportunity to capture on videotape, the actual subsystems during test and have the cognizant engineer explain what we are looking at and the functionality of the subsystem. This product will have a clearly different flavor than the studio lectures, but both have limitations regarding information transfer.

The traditional college lecture-like approach is the popular mode of operation for presentat ions, with viewgraph after viewgraph after viewgraph. "J'hose familiar with the topic gain much, those not vet y familiar find this delivery "boring", and even more so later in '(talking head" videos. ']his results from several factors. The developer/presenter, does not put much time into preparing for his presentation beyond the viewgraphs. Very few individuals will be concerned with methods of making the videotaping more exciting. This is just one more item they arc on the hook to produce They do not want to invest a lot of time, especially since the preparation time is coming from their development, integration and test time. Some of the presenters do not have good presentation skills; they have the expertise, but may not be able to relay it in a "colorful manner". This adds to the painful experience of the novice learner. It takes time to coordinate additional props, computerized animat ion, even locating pictures of the subsystems Developers are in the midst of delivering their subsystems and involved with delivery reviews: making tutorials is not their priority. The information from SAF will suffer as a viewgraph presentation from the lack of time to make the presentation effective. Clearly, this is STEP #1 of our process where information is being captured by the most expeditious means possible and cannot be taken as an end product.

The parallel effort to the information capture, had two purposes. The first was to make the presentations as painless as possible for the presenters and the second was to prototype, at very little cost, an effective approach for immediate information transfer and for long term accessibility. Development of a computer based training (CBT) module was the media selected for investigation. A co-op student was hired as our developer for this six month effort. This forced a short development cycle, which was intentional. We did not want the project to drag on and waste funds if it were not feasible. We also had no actual data in-house as to how much effort the type of product we were shooting for required. The plan was to extract information from the viewgraphs, clip sections of the videotape, cut and paste and come up with an interesting and delightful computer based training product. This product would be guided by inputs and direction from the presenter. We were to place these training modules on a CD-ROM and/or on the internet, provided that by the time this product was to be used frequently, the internet would have software to support the training modules and make it available at everyone's desktop Our co-op participated in the software selection process. We selected Authorware, a multi-platform software package that offered the options to develop the type (d'educational tool we were looking for. The next challenge was for our co-op to learn how to use the software When we were ready for our actual development to begin, only three months were left for the delivery of his product prior to our co-op having to return to school This provided a very valuable lesson learned about the up-front effort required for such a project, even for a "rapid" prototype.

The student was tasked to take the information from the presentations and develop a training module that would be interesting, contain video clips, and question and answers at the conclusion for the flight team member to evaluate their grasp of the subject.. The ideas was that this information could be made accessible to the flight team and with the advancements made. on the WEB, in the future, accessible to the desktop. The issue of maintainability was also considered, that is, as we learned new things about the systems or operations throughout the balance of the spacecraft development, integration, and test as well as the mission, we wanted to update the information. The initial task of developing a tutorial module for the Propulsion System was not completed. The student had to return to school, therefore, we are not quite sure how long the task would have taken to complete. From his assessment, he seemed to be three-qualim"s of the way through in the three months he had to actually develop the module. '

We are re-evacuating STEP#2, our information transfer or educational tool At the present, we will index the information on the video tapes in order to aid flight team members in finding technical information they need immediately on a specific subsystem in a quicker fashion than looking at an entire tape or plowing through test reports or failure analyses. The tapes will be viewed and times noted for each of the topics are covered. The video tapes with the index are then available as a flight team reference and will also be ready for use as video clips are needed for a educational module.

While Authorware is not abandoned, different options are being investigated. Other alternatives include Power Point presentations, talking video (similar to power point but with details on the other page expanding on the bullets), putting the material on the WEB in an educational format and other presentation programs we have available.

GALILEO KNOWLEDGE TOOL

The Galileo Phase 11 Downlink Knowledge Tool (Phase II Flight Software, not the Knowledge Tool) was developed as an information and training resource for Galileo Project team members and the Galileo scientific community. The Galileo team has extensively redesigned the telemetry data handling capabilities of the spacecraft for its two-year orbital tour of Jupiter, which began on December 7, 199S. This new approach became necessary when the spacecraft's high-gain antenna failed to deploy during flight, thereby making the spacecraft's tape recorder and low-gain (backup) antenna the only means of acquiring and sending data to Earth. The Knowledge Tool is therefore an on-line presentation of basic project operational information as well as detailed descriptions of specific data formats, processes, and products as implemented for Phase 11.

The Knowledge Tool was originality envisioned as a multi-media training tooi, delivered on CD ROM, However, considerations of time, possible frequent revision to the design, and the skill level required to implement a full-blown multi-media CD-ROM caused the effort to be scaled back soil-)c]idlat. 'I'he emphasis has now changed from strictly a training resource to that of reference and the sheer dissemination of experts' knowledge. Thus, the Knowledge Tool is implemented in hypertext markup language (HTML) on JPL's gateway-protected domain on the World-wide We%. (The Knowledge Tool is accessible only internally to JPL personnel and to certain univclsity-based project investigators through special computer access arrangements.)

Even though this approach was initially seen as an interim solution, it has turned out to be extremely useful and well-accepted by most project users. Initially, its main customers have been mission controllers (those who monitor and send commands to the spacecraft), and JPL coordinators to the project's science investigators.

Although several other Galileo-related Home Pages already existed, none focused on the details of Phase II data handling. The Knowledge Tool, then, has the dual purpose of providing a convenient reference and operational "toolkit" for day-to-day project operations, as well as a training tool on Galileo downlink data flow and data processing steps. It also includes links to other related reference and training tools that provide a broader context for the data flow process from spacecraft to the end user.

The selection and organization of topics evolved over a few months of usability testing and feedback from Galileo project team members. Certain "Quick Reference Utilities" that proved to be used most often were put near the top of the home page (Figure 1), including an acronym search engine, calendar week-of-year and day-of year conversion tables, and tables showing the time required for radio signals to travel between Earth and the spacecraft.

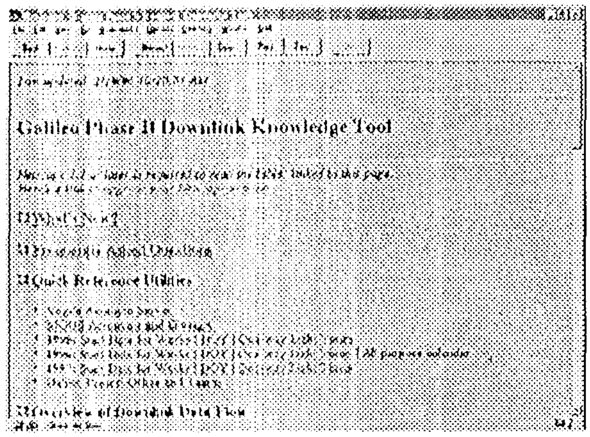

Figure 1. Galileo Knowledge Tool Quick-reference Utilities

Actual data flow information was organized into general and detailed topics (Figure 2), At the overview level, readers are given two ways to access information: using hypertext-linked ("clickable") data flow charts or going directly to a text sub-menu of topics, linked to text descriptions.

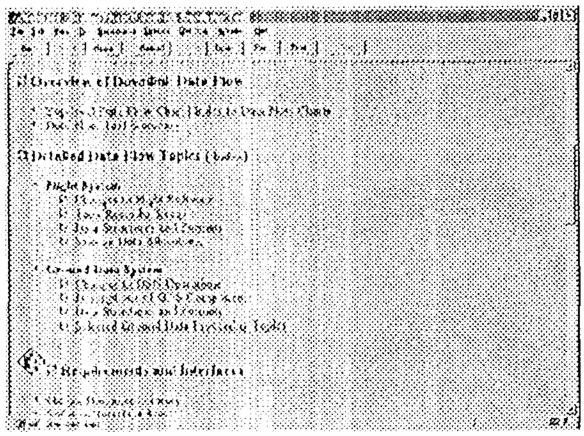

Figure 2. Galileo Knowledge "1'001 General and Detailed Data Flow Information

A series of five flow charts show the flow of data from the spacecraft to the end user. Clicking on a box on the top-level data flow chart (Figure 3) takes the reader to a more detailed data flow chart.

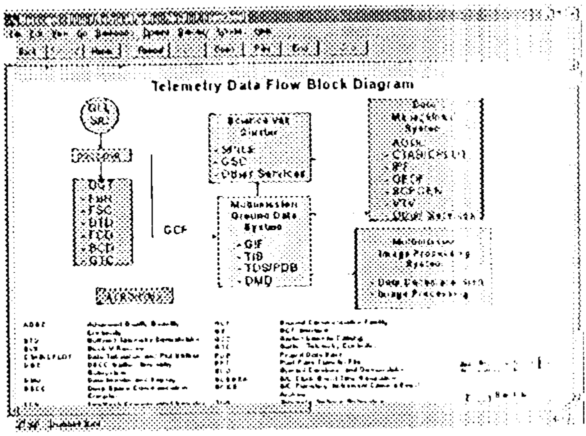

Figure 3. Top-level Data Flow Diagram in Galileo Knowledge Tool

. At this second level, clicking on a box may take the reader to still a third level of data flow chart or to a text description of the box (Figure 4). Alphabetically sorted indexes for text topics and figures are also included on the main menu page.

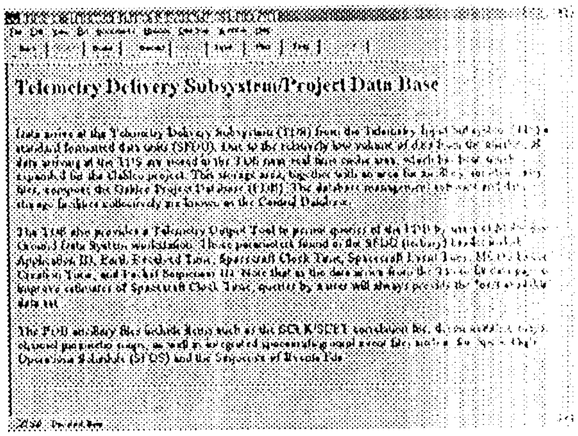

Figure 4. Detailed Text Description Linked to Box on Data Flow Diagram in Galileo Knowledge Tool

The "Detailed Data Flow Topics" are subdivided into Flight System and Ground Data System categories. Other than in the Project documentation itself, it is in these categories that the most detailed, technical information is conveyed. Some of the topics on the home page are subdivided into secondary and tertiary menus (Figure 5).

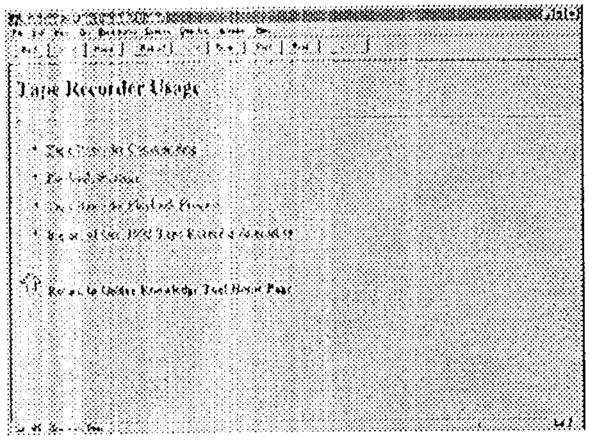

Figure 5. Example of Secondary Menu of Subtopics Related to Galileo Flight System Data Flow on the Galileo Knowledge Tool

The "Requirements and Interfaces" section includes links to detailed Galileo project documentation, as well as very detailed compendiums of data structure and format tables not available on-line anywhere else. This section describes Galileo Phase II data down to the bit level. Most of the project documents are available in Adobe Acrobat .pdf (portable document format) files The Web browser (Netscape, for example) downloads the .pdf file and automatically launches Adobe Acrobat Reader (free software) as a viewer.

The Knowledge Tool home page also includes links to other mission-related home pages and project resources (Figure 6.)

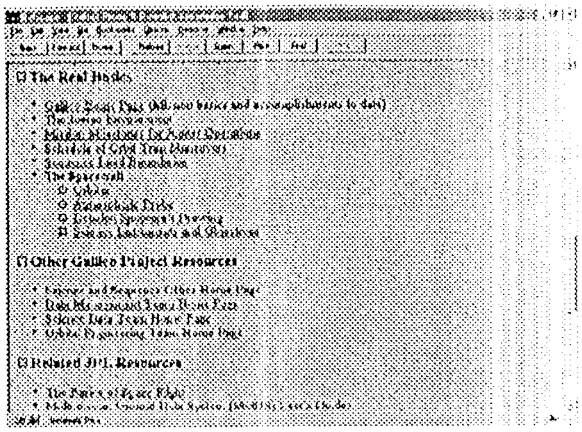

Figure 6. Links to Galileo-related Home Pages and Resources on the Galileo Knowledge Tool Home Page

Finally, links to general resources and other useful (mostly JPL-internal) home pages are included (Figure 7)

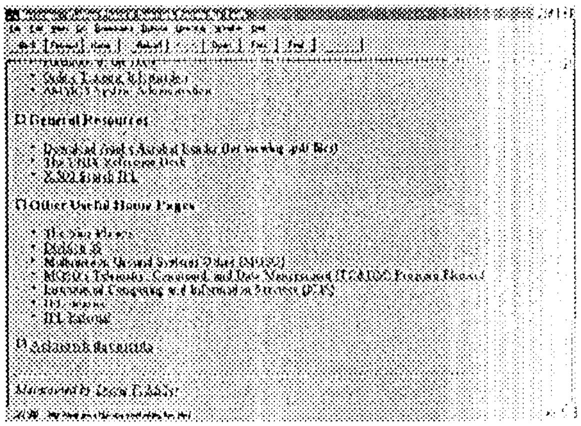

Figure 7. Links on Galileo Knowledge Tool 10 General, Nell-]l]issio]]-)cl:]tcd Resources

Even though the operational changes described in this tool should be in place by June 1996, the nature of space missions is that more will be learned as this new system is implemented. Such new insights are virtually guaranteed. The design of the tool is flexible enough to accommodate new topics and reflect modifications to existing strategies.

Despite the large size of the Galileo project team (over 200), the task of gathering the "latest designs" into the Knowledge Tool, even when they are not formally documented, was achieved with a small core group of busy, yet dedicated individuals. This suggests that a similar tool could be designed for the smaller projects envisioned at JPL.

Future improvements might include hypertext linking, between fries. (Currently, the text descriptions are linked to objects in the figures, but not to each other). The '1'001 designers have been careful not to duplicate complete documents found elsewhere on-line, but a quick reference index with links to the most used of such documents will surely evolve.

DISCOVERY, NEW MILLENNIUM, AND BEYOND

Do we have something that can be useful to space missions which are here now anti just over the horizon? Certainly, if we follow through as intended and learn from our experiences. Clearly, from scratch development ofa CBT tool will not be practical for a small project. We found that the time for the co-op to not oniy learn to use the software authoring system but aiso to learn about spaceflight was a significant factor. However, the tools are now available and we arc developing an in-house expertise in their usc, This means that a ncw project will not nave to start from scratch but can start with someone knowledgeable in the software tools rind in space mission operations.

The development of the lectures to be video taped also provides insight. Those that will provide the best information arc those that involve the end user of the information in the presentation development. The questions that operators will ask when a problem arises are those that must be answered in the presentation. This clearly points to having individuals with actual mission experience involved in this effort so that their expertise can be captured through the questions they ask and then made available to the flight team all through the mission.

The Galileo Knowledge Tool made use of existing documentation arid readily available information on an existing project This says it is never too late to improve the tools you provide the flight team, ()1' particular importance is the relatively low cost and low staffing requirements to put together an impressively significant reference tool.

The message for Discovery, New Millennium, and future projects is to put this effort in your plans. The projects are looking for well qualified, ant] hopefully experienced, people. Sometimes, however, experience is not always available and your plans must take this into account. That is why educational and reference tools can be valuable to these new projects. They will not have the resources to prepare complete flight teams to handle every detail ofa mission However, by judiciously developing the proper tools as the project develops, they will be able to compensate for lack of experience with individuals able to effectively use their cognitive skills supported by project specific educational and reference tools.

The new projects do not need to reinvent the wheel. They can call upon the expertise and the experience gained in the Cassini and Galileo efforts to tailor an information collection process and information transfer tool which is suited to the project's resources. Putting the plan in place early saves resources because information can be captured as it becomes available. Still, even established projects can benefit without an excessive penalty from starting late as the Galileo experience has shown. The bottom line is that the technology and talents are available to make critical information readily available to flight team members, as they need it, so that they do not have to be exper 1s, but can in fact be generalists, and still successfully operate a space exploration mission with fewer operators than we have seen in the past.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion laboratory, California Institute of '1 'echnology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Widdowson, J.M. and Taylor, D., 1992. "Training, for Manned Spaceflight." In *Journal of the British Interplanetary Society*, Vol. 45: "/'7-80.

2. Ayers, T.J. and Bryant, L., 1989. "Training for Spacecraft Technical Analysts." In *Proceedings of the HFS, 33rd Annual Meeting*, 1263-1267.