COMPUTER-BASED INSTRUCTION AND REFERENCE DOCUMENTATION SYSTEM FOR THE ORBIT DETERMINATION PROGRAM

Gerald R. HINTZ
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099

Mark Ryne[1], Michael Watkins[1], Maureen Kenney[2], David Overoye[2]
[1]Jet Propulsion Laboratory, California Institute of Technology
[2]Raytheon, Pasadena, California

ABSTRACT *- The Orbit Determination Program set has been used at the Jet Propulsion Laboratory for nearly half a century to enable precision navigation of interplanetary and earth-orbiting missions and to support a myriad of scientific investigations. Executing this software package successfully is a challenging task for experienced personnel and a daunting one for junior navigators. The effort described in this paper provides a computer-based, web-enabled instructional and reference tool to aid both experienced and beginning personnel in the art of performing orbit determination with this software.*

KEYWORDS: navigation, orbit determination, computer-based instruction, web-enabled instruction

INTRODUCTION

The Orbit Determination Program (ODP) has been developed over a period of 40 years. This software set has enabled accurate navigation[1,2] of NASA's planetary exploration missions to explore every planet in the solar system (except Pluto) and many of their natural satellites, the sun, comets Halley, Giacobini-Zinner and Borrelly, and asteroids Ida, Gaspra, Mathilde, Eros, Annefrank, and Braille. This software set has provided the navigation function for more than 150 missions, including Mariners 2, 4-7, 9-10, Rangers 5, 7-9, Surveyors 1, 3, 5-7, Lunar Orbiters 1-5, Pioneers 6-13, Vikings 1-2, Voyagers 1-2, ISEE-3, Vegas 1-2, Sakigake, Giotto, Suisei, Magellan, Galileo, HITEN, Hubble, Ulysses, TOPEX/Poseidon, Mars Observer, NEAR, Mars Pathfinder, Space VLBI (VSOP), Mars Global Surveyor, Cassini-Huygens, Lunar Prospector, Deep Space 1, Mars Climate Orbiter, Mars Polar Lander/Deep Space 2, Stardust, Shuttle Radar Topography Mission (SRTM), 2001 Mars Odyssey, Genesis, Gravity Recovery and Climate Experiment (GRACE), Space Infrared Telescope (SIRTF), and Mars Exploration Rovers 1-2, plus NIMBUS 7, LAGEOS 2, ROSAT, AMPTE-IRM, AMPTE-CCE, PHOBOS 1-2, GEOTAIL, Clementine, and the Space Flyer Unit (SFU). Hence, this software has supported national and international missions for the Jet Propulsion Laboratory (JPL), Langley Research Center, Ames, Goddard Space Flight Center, the European Space Agency (ESA), the German Space Operations Center (GSOC), Applied Physics Laboratory (APL), the Space Research Institute (IKI), the National Space Development Agency of Japan (NASDA), The Institute of Space and Astronomical Science (ISAS), and the National Research Laboratory (NRL).

The ODP software has also supported significant scientific investigations in celestial mechanics, relativity, geodesy, ephemerides, and celestial reference frames. Many of the scientific discoveries of NASA's planetary exploration program have been dependent on accurate navigation provided through use of this software. Some examples of the discoveries made possible by using this software include determining high order gravity fields for Venus[3], Mars[4], the earth, and the moon[5], near real-time gravity modeling of the asteroid Eros[6], lunar mascons from Lunar Orbiter V data[7], topographical features[8] of Venus and Mars, planetary rotation periods[3,9,10], planetary and satellite mass determinations[3,4,5], atmospheric structure for Venus and Mars, relativity model confirmation, geophysical parameters determination[6,9], and geodesy in general for the planets[9,10,11]. The ODP has also been used to make corrections to the planetary and natural satellite ephemerides.

The software set, including the trajectory modeling and propagation programs (DPTRAJ for Double Precision Trajectory) and the orbit estimation and prediction set (ODP for Orbit Determination Program), consists of 2.0 million lines of code with 16 major programs, 350,000 input parameters, 151 utility programs, 55 libraries, 196 scripts, and 7516 files. Performing the various tasks that are a part of the orbit determination effort involves executing selected subsets of this system. Hence, running this software package is a challenging task for experienced personnel and a daunting one for junior navigators.

This paper describes an effort to provide an instructional and reference tool utilizing web-based technology to minimize the time and financial costs involved in training both experienced and beginning personnel in the art of performing orbit determination with this software. The paper includes the list of requirements and goals of the computer-based instructional (CBI) tool, its development, its use, and the lessons learned to date.

1. REQUIREMENTS AND GOALS FOR THE COMPUTER-BASED INSTRUCTIONAL SYSTEM

The need for the instructional tool was driven by several factors, including the increasing complexity of orbit determination (OD) with the ever present need to avoid operational risk and to contain costs. Another factor was the institutional change from supporting a small number of large flight missions with large navigation teams to supporting a large number of small missions with small navigation teams. The driving requirements of the development effort were to:

(a) Reduce dependence on experienced personnel for provision of training activities. New navigators traditionally acquire experience and instruction with the ODP through a mentoring process, which has proven to be successful. However, mentoring new personnel, while a critical function, is also time-consuming. Therefore, it is important to develop tools to aid this task.

(b) Capture and manage knowledge. As senior personnel retire from active participation in the field, it becomes imperative to capture the accomplishments and experience of the first generation of interplanetary navigators to provide a guide for their replacements.

(c) Reduce the time required to train a new navigator for flight operations. In the past, the training period for a new employee could extend to a year or beyond. It is essential, in this era of many small missions, that the training be accomplished more quickly than in the past.

(d) Reduce training costs. Training applies to all personnel, since it must include the full-scale training of an inexperienced person as well as provide the occasional reference or refresher required by experienced navigators. Providing separate training for these two groups is expensive to develop, maintain, and update. Thus, one goal of the computer-based instruction (CBI) was that it provide for the needs of both groups.

(e) Manage risk. It is necessary to reduce risks from operational errors. Standardizing the training material in order to provide a common reference for all navigators is a key element in risk reduction in a multimission environment.

(f) Provide a tool that is flexible enough to cope with the constantly changing spacecraft, missions and associated parameters. Orbit determination software evolves to meet the requirements specified by each mission and changing spacecraft parameters throughout each mission.

(g) Provide a system that is easily maintained and updated under configuration control with efficient and secure accessibility.

Additional design goals were also considered as follows:

(a) The ideal CBI system would make it possible for personnel to move from project to project seamlessly.

(b) A system that could easily and efficiently be applied to the next generation of orbit determination software would preserve the capital investment in the program and infrastructure.

(c) The training tool would serve as a vehicle for introducing Navshell, an ODP execution processor. Navshell allows standardized inputs for multiple missions with diverse requirements and supports a uniform interface for numerous operational scenarios such as a single batch sequential filter, a multi-batch stochastic filter, and differential and optical data types. This flexible tool can provide standardized scripts for novice users or production runs while retaining the ability to use the most advanced and generalized capabilities of the software suite.

To meet these requirements and goals, it was determined to be necessary to provide both an instructional "how to" tool for new navigators and a reference system for experts. It was also ascertained that another characteristic of the system is that it must emphasize the application of the orbit determination process. This tool was not to be a comprehensive description of underlying principles of physics or mathematical formulations, but rather a "how to" guide.

2. DEVELOPMENT OF THE COMPUTER-BASED INSTRUCTIONAL SYSTEM

Knowledge Capture

Inherited Training Tools and Materials

The documentation for the ODP consisted of four very large manuals, sectioned by areas such as Programs, Utilities, and Parameters, without cross-linking between volumes or sections. These manuals had been converted to static HTML and were available online. An institutional search would point to pages containing similar material, but such a search was not streamlined. Additional documentation was added over the years. This information often took the form of a What's New web page that included a list of changes, additions and corrections relative to the original documentation. Manual pages were available for new utilities within the directories where those utilities were stored.

Other input included institutional spacecraft navigation procedures and operational procedures developed for navigating the Cassini spacecraft, including those for updating media calibration files, iterating runs to obtain a converged solution, generating B-plane plots, updating tracking data logs, creating stochastic or residual plots, and creating a summary print.

Orbit Determination Workshop

An orbit determination workshop was conducted as the first step in developing a CBI tool. This workshop, spread over one week, helped the CBI developers understand the ODP and the inherited documents. One presentation entitled, "Using the ODP for Pre-Flight Analysis and Cruise OD," provided an overview, covered the following tasks:

1. Obtaining observation data.
2. Updating the spacecraft state and its predicted trajectory, using the observations in task 1.
3. Comparing the predicted trajectory outcome in task 2 and the desired target and computing a trajectory correction maneuver, if necessary.

This presentation also considered these three navigation tasks in more detail, including the process of obtaining radiometric range and Doppler data from the Deep Space Network (DSN), ephemeris generation, calibration of media and platform parameters, the parameter estimation of a spacecraft state[12], the mapping of the navigation errors to the target B-plane, and OD covariance analyses. The last of these tasks may be performed years before launch to judge the feasibility and limitations of a particular baseline trajectory.

Another presentation, "SIGMA: The Filter and Mapping Module of the ODP," included the mathematical fundamentals of this software routine. "Trajectory Integration" covered integration control, gravity modeling and perturbing accelerations, and the generation of partial derivatives of the spacecraft state with respect to requested parameters. The last presentation, "Making a Usable ODP System," discussed the ODP heritage, main programs, input, file types, and the use of the Navshell script to make multiple program runs automatically, handle file input/output connections, catch input errors before execution, detect execution failures, and catalog results.

Interviews

It was determined that interviewing the navigators was a necessary way to understand the ODP. Group meetings were considered and rejected because each navigator had developed a separate method for using the ODP. A group meeting would require a lengthy discussion of each of these techniques, rather than a more general discussion of the common process flow of the ODP. Interviews began with the Navigation management staff, proceeded to senior navigators, and concluded with a series of interviews of junior navigators and program developers.

The managers and senior navigators provided several elements to the ODP-CBI development process. They were able to articulate how they use the ODP to perform navigational tasks, thus helping to define the ODP processes. The senior level personnel were also helpful in defining how they mentor new employees – what they tell the junior navigators and how they elaborate on the documentation. This information in turn led to the development of our knowledge capture tools, as we began to understand the scope of the institutional knowledge that was available. Finally, this group was able to define for us what they needed in a reference tool and to help us to make the tools more useful for all orbit determination analysts.

Junior navigators were interviewed to gain insight into how they were learning to use the ODP and what tools would help them to learn more quickly. Through these interviews, we were able to define some of the examples that should be available, such as sample case studies and setup files.

To gain a real understanding of the program, we interviewed both users of the ODP and software developers. In many cases, the developers were able to provide some insight into the iterative nature of the changes in ODP. Users were able to help us to develop the high level and lower level process diagrams of the ODP.

As we interviewed the ODP personnel, we were looking for the actual application of the program suite – how it is used, who uses it, when and in what context specific pieces of the program are invoked. At the same time, however, it was useful for the navigators to provide us with some theoretical background to form a context for the application.

Knowledge Synthesis

Upon completion of the initial knowledge capture phase of the ODP-CBI, the Knowledge Synthesis phase began. It was necessary to determine how best to organize the data to make it accessible to navigators and to make the system extensible, as changes in the program were introduced and as additional knowledge about the ODP was added to the system.

ODP-CBI Overall Organization

As a first step, the high level flow of the ODP process was graphically depicted as the top or entry point into the CBI system. This screen is shown in Fig. 1.

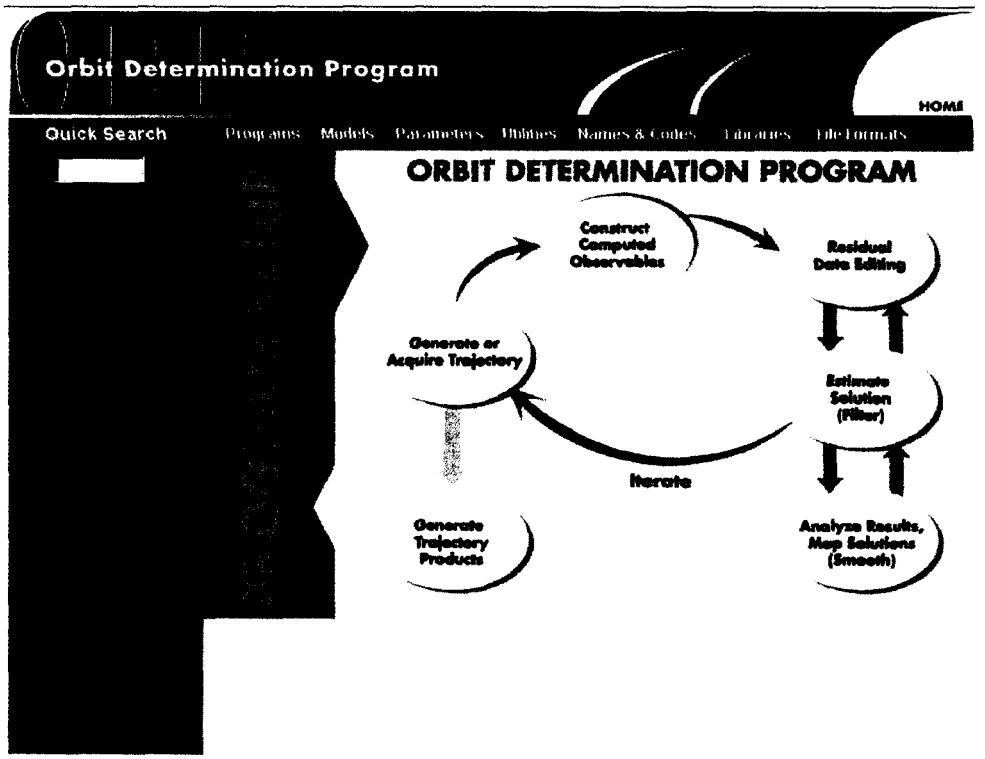

Fig. 1 - High-level Flow of ODP Process

This flow is a clickable map, where each bubble in the flow can be selected individually. The second-level flow is then exposed to the navigator.

Program Setup is a precursor to the orbit determination process and is essential to the successful use of the program. Therefore, it was added to the top-level flow. Selecting the Setup option exposes a variety of information about the pre-execution steps. Included here are incorporated lessons, seminar presentations, and sample files for program setup. Also included are case studies of missions, showing how to run the ODP. This screen is shown in Fig. 2.

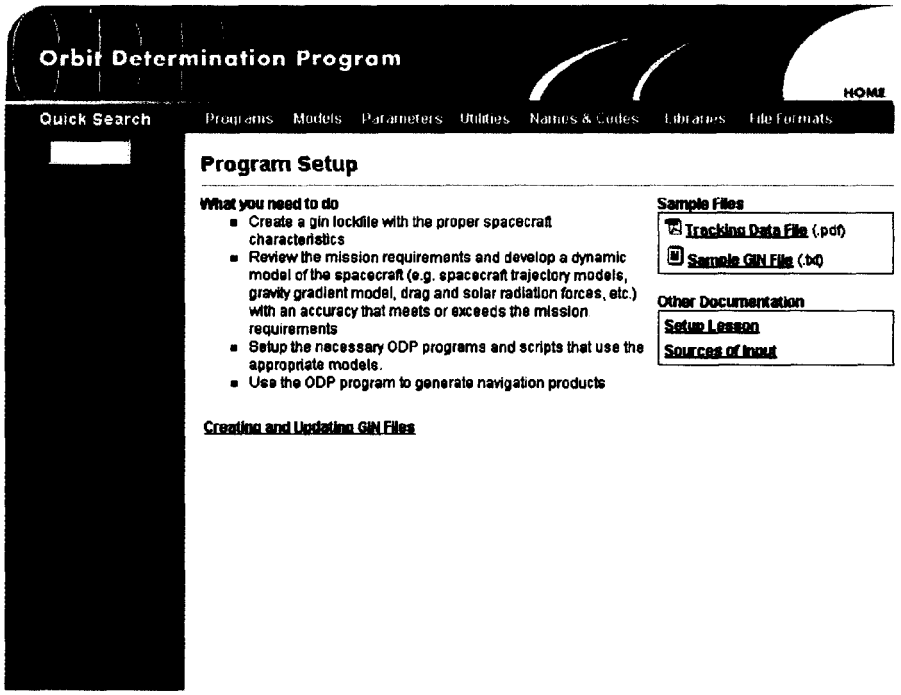

Fig. 2 – Program Setup

Selection of a process on the High-level Flow of ODP Process screen reveals a drill down for detail. This detail includes a process abstract and flow diagram with links to more information. The screen for Generate or Acquire Trajectory is shown in Fig. 3 as a sample.

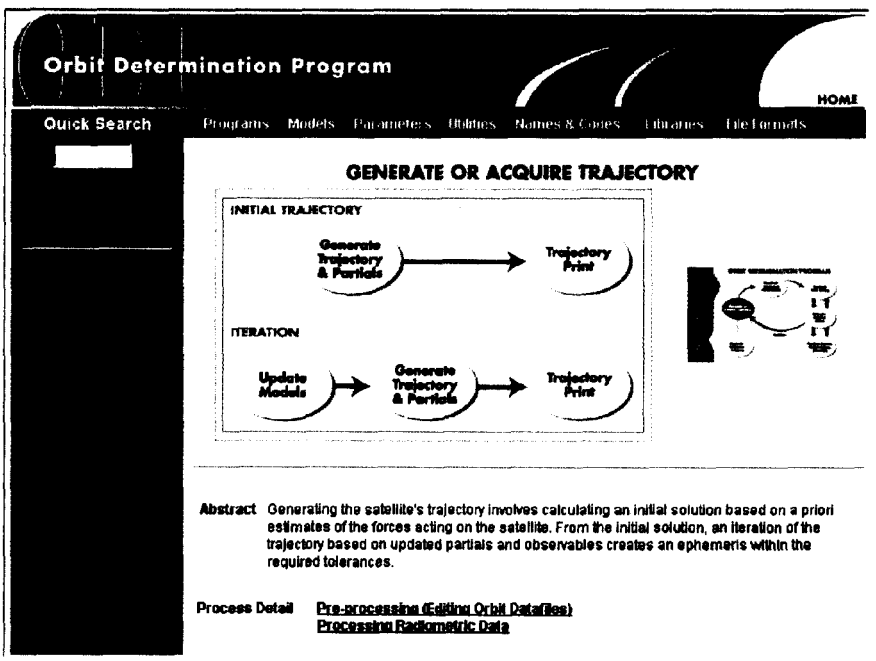

Fig. 3 - Second Level Flow

Incorporation of Tutorials

The eight-week seminar series on Navshell was captured and incorporated into the ODP-CBI. Links within the seminar series documentation include agenda, homework, audio/video screen capture of the demonstrations, and PowerPoint presentations for each of the sessions. Experienced navigators can use the seminar series as refresher information. New navigators can use the series as a beginning training series. By capturing the seminar series, the navigation group was able to reduce the frequency of instructor-led courses for new personnel. This screen is shown in Fig. 4.

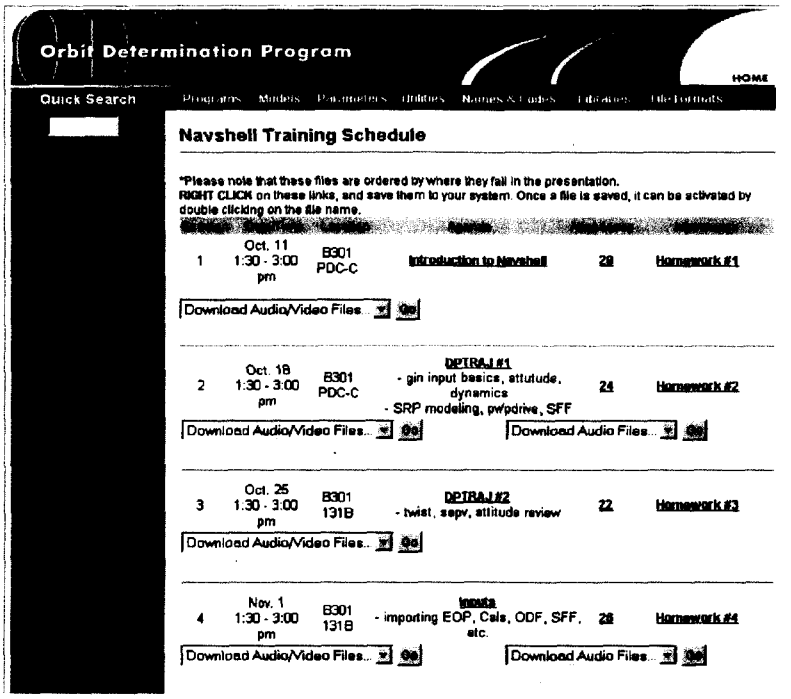

Fig. 4 – Navshell Seminar Series

Knowledge Display

Web-based Instruction

The computer-based instruction program that was developed for the ODP is web-based, reducing the cost of dissemination. Training can now be available on any desktop that includes a standard web browser among its tool set. No additional software (other than free web plug-ins for multi-media display) is necessary, simplifying the distribution of the material, while minimizing capital expenditures, and assuring that the CBI represents the current version of the operational ODP software. Web-based CBI thus makes full use of new technology to enhance the delivery of training services.

Links to Existing Controlled Documentation, Labels and Descriptors – a Database Solution

The database-backed design of the ODP CBI offers the advantage of a cross-referenced and cross-linked display of existing documentation. It thus provides an enhanced documentation set for the experienced navigators. The database design also provides a simple way to organize and extend the document set and immediately integrate new material into the context of the existing material. This feature greatly reduces the possibility that the user will overlook additions to the documentation. Now, through unified search and contextual display, the new material can be displayed alongside the existing information on that topic. An example of this screen is shown in Fig. 5.

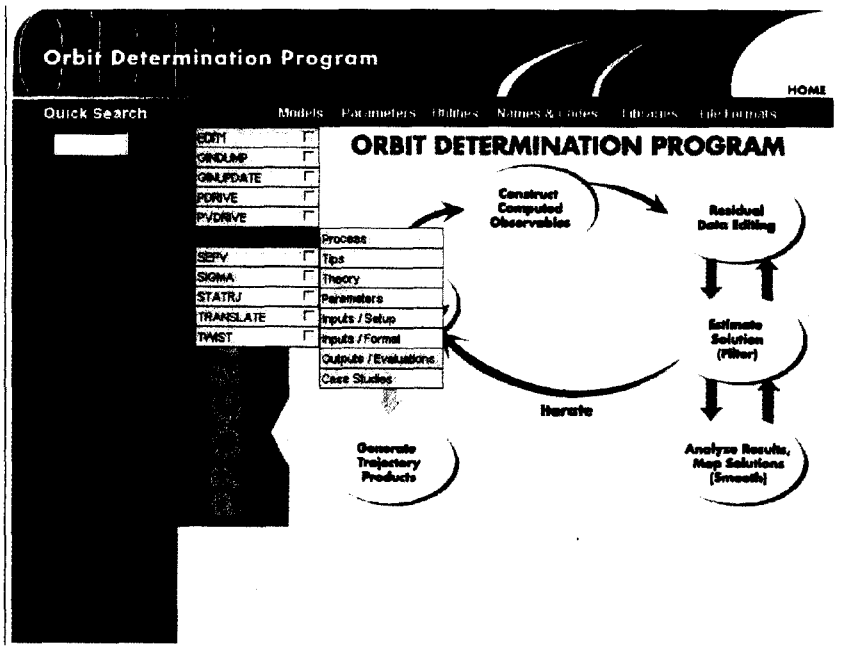

Fig. 5 – Cross-linking and Referencing of ODP Documentation

Descriptive or Narrative Wrapper for Each Model or Process in ODP-Aided Navigation
This feature helps the novice user by providing a description of the function-selected item. Other information places the item in the overall context of the orbit determination process.

Custom Multi-media Elements
Some areas of the ODP are difficult to describe or teach as simple web pages or single images. For these cases, the ODP-CBI tool employs streaming media. This style of presentation is similar to watching a mentor and has the advantage of showing an entire process. Supporting documents reveal links between ODP parameters and the under equations they represent. A typical screen is shown in Fig. 6.

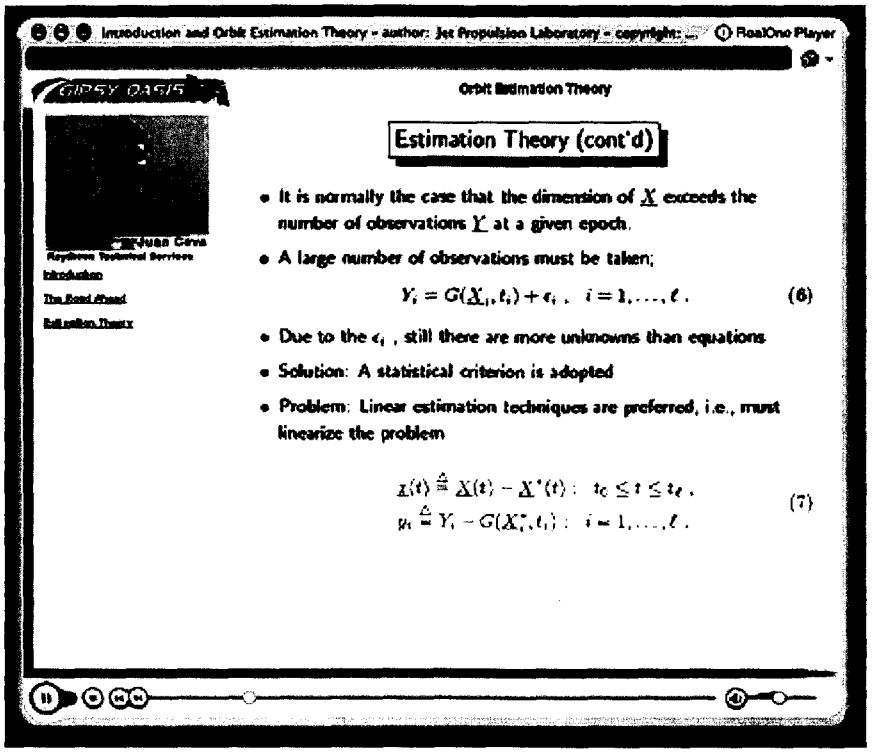

Fig. 6 – Streaming Media Capture of Subject Matter Expert Seminars

This method also shows the proper usage of software with graphical user interfaces. A graphical, interactive navigation data editor can employ lasso grabbing, data deletion, automatic, and interactive re-scaling. Other features include data and case selection and use of colors and symbols to help identify data sources and problems. Streaming media allows a mentor to talk about a process and show the results simultaneously to the student. An example of this screen is shown in Fig. 7.

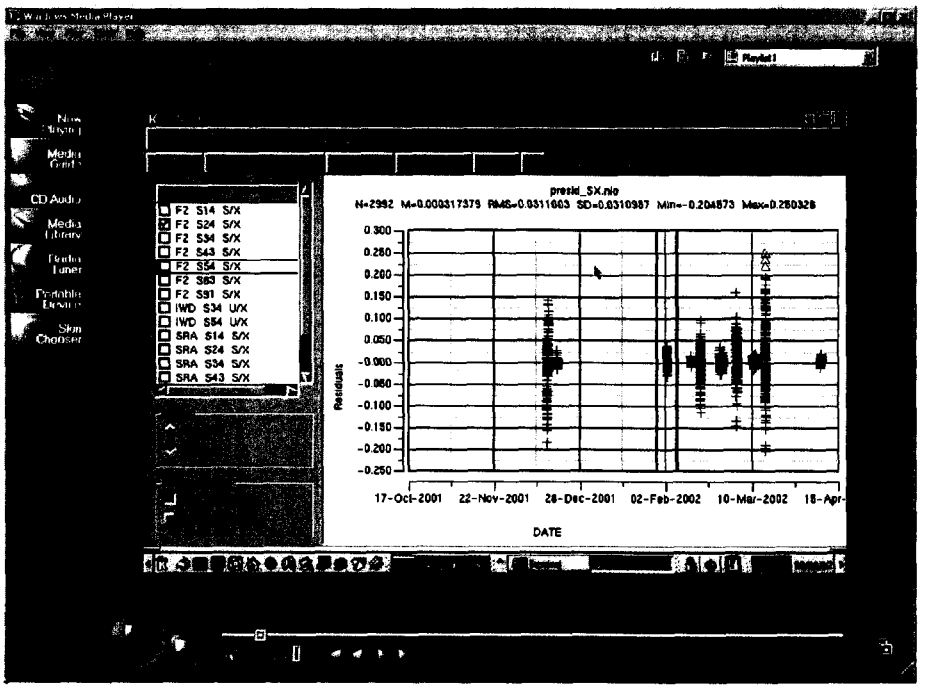

Fig. 7 – Screen-capture of Navshell Seminar Series

Index and Search Capabilities

Search capabilities include a quick search, which produces a comprehensive list of all occurrences of key words. An advanced search capability, as shown in Fig. 8, provides a way for the navigator to select the subset of material that he or she wants to view. For instance, the key word search may be limited to the program descriptions containing that word, providing a more focused approach to data mining. Once a search result is selected, the cross-links are then exposed for the navigator. These might include parameters, utilities and models that are also associated with that key word.

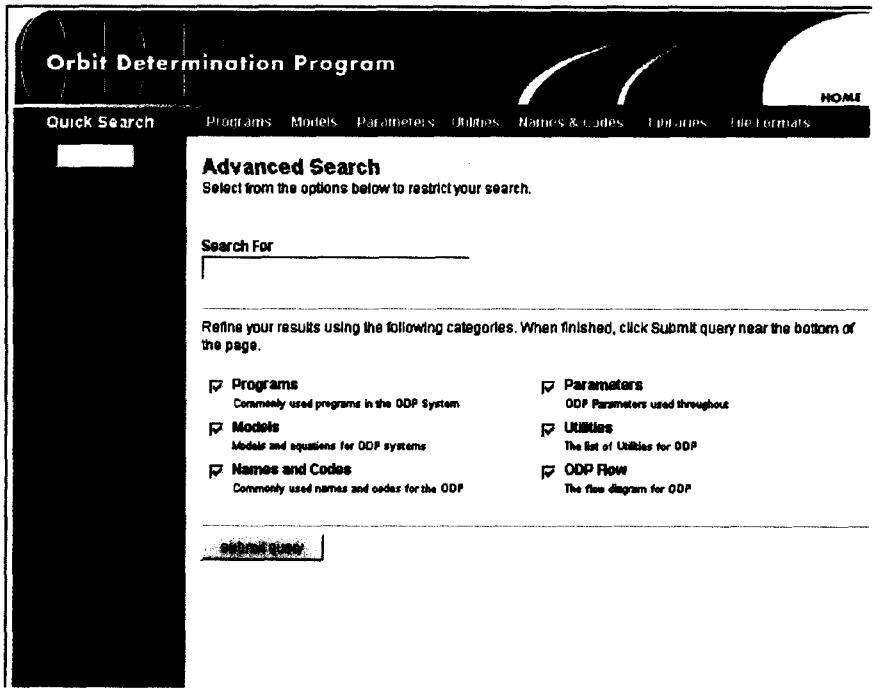

Fig. 8 – Advanced Search Capabilities

Selected Working Examples, Case Studies, and Exercises

Case studies of representative missions were included as linked documents within the ODP-CBI tools. It is intended that these case studies will be further cross-linked to specific processes to demonstrate how the ODP is applied in a practical example.

Tips, Tricks and Frequently Asked Questions (FAQs)

Built into the ODP-CBI tool is the ability to capture expert knowledge as "Tips" in the context of the ODP – for example, associated with a particular program or model or parameter. These tips are entered into a database and referenced in the context of their topic and category. They are also exposed at the top level on a categorized list. The ability to capture expert knowledge and instantly expose it to the user community is an example of the use of technology to provide innovative training tools. In this case, the tips can supplement the mentor relationship and extend it beyond the one-on-one training that is the usual scenario. This information enables the novice and senior engineer to troubleshoot a problem and de-mystify the common pitfalls of orbit determination. This screen is shown in Fig. 9.

The instructional tool provides a set of guidelines[13] for doing orbit determination as shown in Fig. 9. Each guideline is a link to more detailed information.

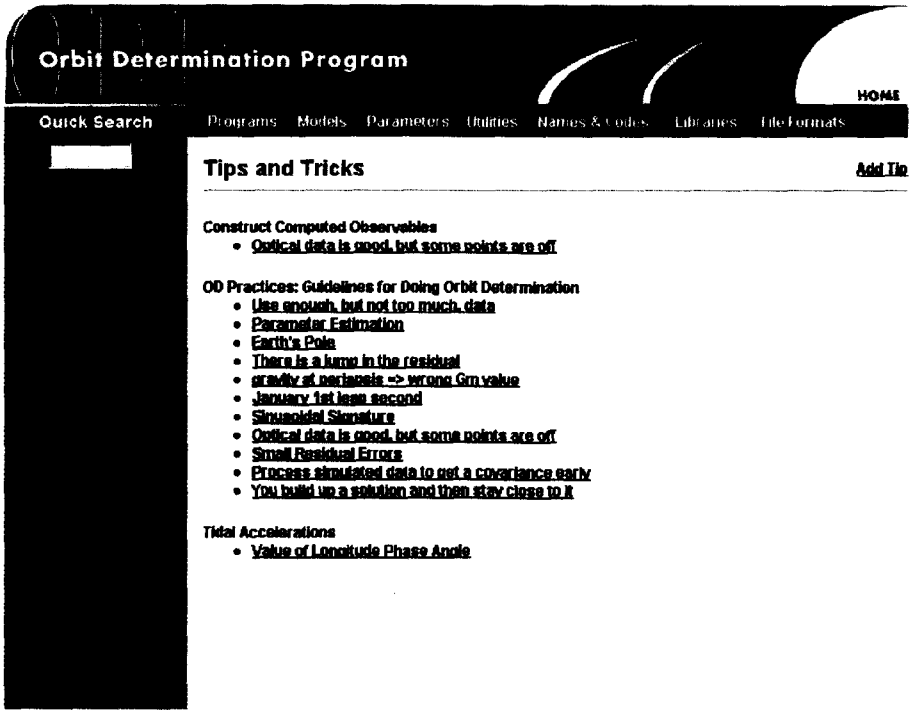

Fig. 9 – Tips, Tricks and FAQs

Verification of Knowledge System and Content

Review of CBI System and Materials by Navigation Experts
Cognizant programmers have reviewed the file formats and parameter descriptions. The changes that are identified in this process are being implemented as part of the ongoing maintenance phase.

Feedback from Experts and from Users New to the ODP
A formal mechanism to capture feedback from users was incorporated into the ODP CBI. This feedback is directed to the developers for bug fixes and for program enhancement. Such feedback can be supplied via user-initiated pop-up as shown in Fig. 10 or Bugzilla[14], a formal anomaly reporting system.

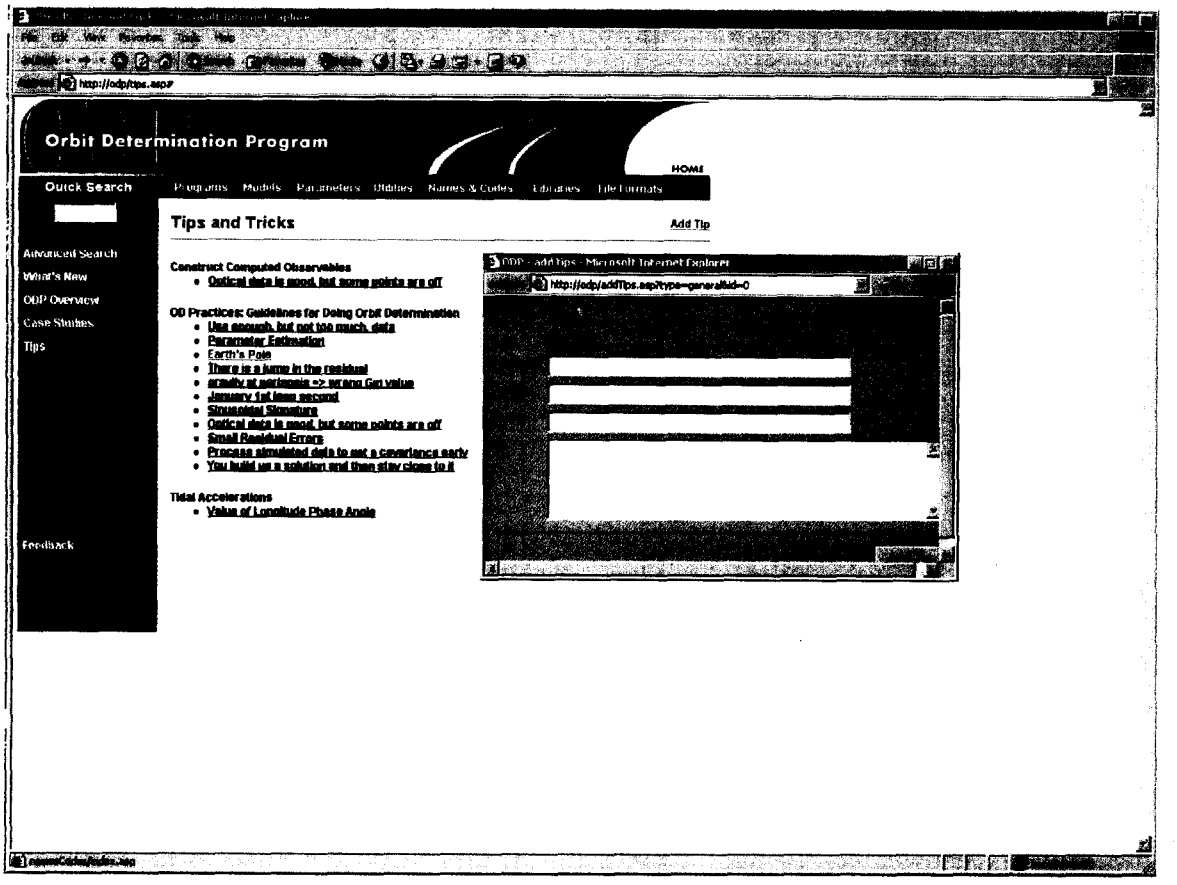

Fig. 10 – Capturing Subject Matter Expert Advice within the Context of the ODP Process

3. LESSONS LEARNED

The lessons learned to date are:

(a) Learning how to run the ODP is not the same as learning how to steer an antenna. One attempt to develop a CBI tool followed the approach that training could be accomplished as one describes the well-defined, step-by-step operation of steering an antenna. However, this approach was soon abandoned because it is ineffective for the problem of selecting the optimal strategy for doing orbit determination. For example, Reference 2 considers several OD strategies that were employed for the Mars Odyssey spacecraft.

(b) Developing a CBI system for a complex subject is an iterative process that requires frequent reviews of progress and design decisions.

(c) Collecting, structuring and distributing the history of knowledge gained over the last 40 years is a formidable task. It requires a variety of methods and a great deal of patience and persistence.

4. CONCLUDING REMARKS

Tasks the Analyst Can Attack Using This Tool
The beginning analyst will use this tool to learn the step-by-step procedure for running the ODP. In this learning process, the analyst will be aided by the working examples of process flow and input and output, the tutorials (e.g., the set of Navshell tutorials), and the information provided about the program at varying depths of viewing.

The experienced analyst will use this tool to answer specific questions concerning individual parameters, parameter types and defaults, array sizes and syntax. One can then follow readily accessible links to find related parameters and investigate their interactions.

Both the beginner and the expert analysts will seek the answer to a myriad of specific questions such as:

How does one model the physical spacecraft structure?
How does one build a solar pressure model?
How does one deal with small forces?
How does one iterate on stochastic parameters?
How does one process differenced Doppler data?
What is a B-Plane?

All users will also benefit from the tips and tricks reference. This feature provides general ground rules, and common pitfalls, mistakes and errors. Also available are links to a database containing translations of error messages and error numbers. This information, accessible via index and search capabilities, will help to de-mystify the OD process.

Results
The CBI tool has been described as a "mature product." It has been released for use by JPL personnel for pre-flight analyses and operational activities. Metrics will measure its effectiveness in meeting the requirements listed in Section 1. Maintenance in response to user comments and suggestions is continuing.

Future Enhancements
The current version of the CBI tool considers range and Doppler data. Possible future enhancements would be to add the processing of other data types such as delta-DOR (differenced differential one-way range), launch angles, and optical navigation measurements. Additional functionality may include a method for monitoring and approving user tips, web-based access to update content as required, parsing of additional case studies within the tool, and expansion of the tool to include new software developments.

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KEYWORDS: navigation, orbit determination, computer-based instruction, web-enabled instruction

INTRODUCTION

The Orbit Determination Program (ODP) has been developed over a period of 40 years. This software set has enabled accurate navigation[1,2] of NASA's planetary exploration missions to explore every planet in the solar system (except Pluto) and many of their natural satellites, the sun, comets Halley, Giacobini-Zinner and Borrelly, and asteroids Ida, Gaspra, Mathilde, Eros, Annefrank, and Braille. This software set has provided the navigation function for more than 150 missions, including Mariners 2, 4-7, 9-10, Rangers 5, 7-9, Surveyors 1, 3, 5-7, Lunar Orbiters 1-5, Pioneers 6-13, Vikings 1-2, Voyagers 1-2, ISEE-3, Vegas 1-2, Sakigake, Giotto, Suisei, Magellan, Galileo, HITEN, Hubble, Ulysses, TOPEX/Poseidon, Mars Observer, NEAR, Mars Pathfinder, Space VLBI (VSOP), Mars Global Surveyor, Cassini-Huygens, Lunar Prospector, Deep Space 1, Mars Climate Orbiter, Mars Polar Lander/Deep Space 2, Stardust, Shuttle Radar Topography Mission (SRTM), 2001 Mars Odyssey, Genesis, Gravity Recovery and Climate Experiment (GRACE), Space Infrared Telescope (SIRTF), and Mars Exploration Rovers 1-2, plus NIMBUS 7, LAGEOS 2, ROSAT, AMPTE-IRM, AMPTE-CCE, PHOBOS 1-2, GEOTAIL, Clementine, and the Space Flyer Unit (SFU). Hence, this software has supported national and international missions for the Jet Propulsion Laboratory (JPL), Langley Research Center, Ames, Goddard Space Flight Center, the European Space Agency (ESA), the German Space Operations Center (GSOC), Applied Physics Laboratory (APL), the Space Research Institute (IKI), the National Space Development Agency of Japan (NASDA), The Institute of Space and Astronomical Science (ISAS), and the National Research Laboratory (NRL).

The ODP software has also supported significant scientific investigations in celestial mechanics, relativity, geodesy, ephemerides, and celestial reference frames. Many of the scientific discoveries of NASA's planetary exploration program have been dependent on accurate navigation provided through use of this software. Some examples of the discoveries made possible by using this software include determining high order gravity fields for Venus[3], Mars[4], the earth, and the moon[5], near real-time gravity modeling of the asteroid Eros[6], lunar mascons from Lunar Orbiter V data[7], topographical features[8] of Venus and Mars, planetary rotation periods[3,9,10], planetary and satellite mass determinations[3,4,5], atmospheric structure for Venus and Mars, relativity model confirmation, geophysical parameters determination[6,9], and geodesy in general for the planets[9,10,11]. The ODP has also been used to make corrections to the planetary and natural satellite ephemerides.

The software set, including the trajectory modeling and propagation programs (DPTRAJ for Double Precision Trajectory) and the orbit estimation and prediction set (ODP for Orbit Determination Program), consists of 2.0 million lines of code with 16 major programs, 350,000 input parameters, 151 utility programs, 55 libraries, 196 scripts, and 7516 files. Performing the various tasks that are a part of the orbit determination effort involves executing selected subsets of this system. Hence, running this software package is a challenging task for experienced personnel and a daunting one for junior navigators.

This paper describes an effort to provide an instructional and reference tool utilizing web-based technology to minimize the time and financial costs involved in training both experienced and beginning personnel in the art of performing orbit determination with this software. The paper includes the list of requirements and goals of the computer-based instructional (CBI) tool, its development, its use, and the lessons learned to date.

1. REQUIREMENTS AND GOALS FOR THE COMPUTER-BASED INSTRUCTIONAL SYSTEM

The need for the instructional tool was driven by several factors, including the increasing complexity of orbit determination (OD) with the ever present need to avoid operational risk and to contain costs. Another factor was the institutional change from supporting a small number of large flight missions with large navigation teams to supporting a large number of small missions with small navigation teams. The driving requirements of the development effort were to:

(a) Reduce dependence on experienced personnel for provision of training activities. New navigators traditionally acquire experience and instruction with the ODP through a mentoring process, which has proven to be successful. However, mentoring new personnel, while a critical function, is also time-consuming. Therefore, it is important to develop tools to aid this task.

(b) Capture and manage knowledge. As senior personnel retire from active participation in the field, it becomes imperative to capture the accomplishments and experience of the first generation of interplanetary navigators to provide a guide for their replacements.

(c) Reduce the time required to train a new navigator for flight operations. In the past, the training period for a new employee could extend to a year or beyond. It is essential, in this era of many small missions, that the training be accomplished more quickly than in the past.

(d) Reduce training costs. Training applies to all personnel, since it must include the full-scale training of an inexperienced person as well as provide the occasional reference or refresher required by experienced navigators. Providing separate training for these two groups is expensive to develop, maintain, and update. Thus, one goal of the computer-based instruction (CBI) was that it provide for the needs of both groups.

(e) Manage risk. It is necessary to reduce risks from operational errors. Standardizing the training material in order to provide a common reference for all navigators is a key element in risk reduction in a multimission environment.

(f) Provide a tool that is flexible enough to cope with the constantly changing spacecraft, missions and associated parameters. Orbit determination software evolves to meet the requirements specified by each mission and changing spacecraft parameters throughout each mission.

(g) Provide a system that is easily maintained and updated under configuration control with efficient and secure accessibility.

Additional design goals were also considered as follows:

(a) The ideal CBI system would make it possible for personnel to move from project to project seamlessly.

(b) A system that could easily and efficiently be applied to the next generation of orbit determination software would preserve the capital investment in the program and infrastructure.

(c) The training tool would serve as a vehicle for introducing Navshell, an ODP execution processor. Navshell allows standardized inputs for multiple missions with diverse requirements and supports a uniform interface for numerous operational scenarios such as a single batch sequential filter, a multi-batch stochastic filter, and differential and optical data types. This flexible tool can provide standardized scripts for novice users or production runs while retaining the ability to use the most advanced and generalized capabilities of the software suite.

To meet these requirements and goals, it was determined to be necessary to provide both an instructional "how to" tool for new navigators and a reference system for experts. It was also ascertained that another characteristic of the system is that it must emphasize the application of the orbit determination process. This tool was not to be a comprehensive description of underlying principles of physics or mathematical formulations, but rather a "how to" guide.

2. DEVELOPMENT OF THE COMPUTER-BASED INSTRUCTIONAL SYSTEM

Knowledge Capture

Inherited Training Tools and Materials

The documentation for the ODP consisted of four very large manuals, sectioned by areas such as Programs, Utilities, and Parameters, without cross-linking between volumes or sections. These manuals had been converted to static HTML and were available online. An institutional search would point to pages containing similar material, but such a search was not streamlined. Additional documentation was added over the years. This information often took the form of a What's New web page that included a list of changes, additions and corrections relative to the original documentation. Manual pages were available for new utilities within the directories where those utilities were stored.

Other input included institutional spacecraft navigation procedures and operational procedures developed for navigating the Cassini spacecraft, including those for updating media calibration files, iterating runs to obtain a converged solution, generating B-plane plots, updating tracking data logs, creating stochastic or residual plots, and creating a summary print.

Orbit Determination Workshop

An orbit determination workshop was conducted as the first step in developing a CBI tool. This workshop, spread over one week, helped the CBI developers understand the ODP and the inherited documents. One presentation entitled, "Using the ODP for Pre-Flight Analysis and Cruise OD," provided an overview, covered the following tasks:

1. Obtaining observation data.
2. Updating the spacecraft state and its predicted trajectory, using the observations in task 1.
3. Comparing the predicted trajectory outcome in task 2 and the desired target and computing a trajectory correction maneuver, if necessary.

This presentation also considered these three navigation tasks in more detail, including the process of obtaining radiometric range and Doppler data from the Deep Space Network (DSN), ephemeris generation, calibration of media and platform parameters, the parameter estimation of a spacecraft state[12], the mapping of the navigation errors to the target B-plane, and OD covariance analyses. The last of these tasks may be performed years before launch to judge the feasibility and limitations of a particular baseline trajectory.

Another presentation, "SIGMA: The Filter and Mapping Module of the ODP," included the mathematical fundamentals of this software routine. "Trajectory Integration" covered integration control, gravity modeling and perturbing accelerations, and the generation of partial derivatives of the spacecraft state with respect to requested parameters. The last presentation, "Making a Usable ODP System," discussed the ODP heritage, main programs, input, file types, and the use of the Navshell script to make multiple program runs automatically, handle file input/output connections, catch input errors before execution, detect execution failures, and catalog results.

Interviews

It was determined that interviewing the navigators was a necessary way to understand the ODP. Group meetings were considered and rejected because each navigator had developed a separate method for using the ODP. A group meeting would require a lengthy discussion of each of these techniques, rather than a more general discussion of the common process flow of the ODP. Interviews began with the Navigation management staff, proceeded to senior navigators, and concluded with a series of interviews of junior navigators and program developers.

The managers and senior navigators provided several elements to the ODP-CBI development process. They were able to articulate how they use the ODP to perform navigational tasks, thus helping to define the ODP processes. The senior level personnel were also helpful in defining how they mentor new employees – what they tell the junior navigators and how they elaborate on the documentation. This information in turn led to the development of our knowledge capture tools, as we began to understand the scope of the institutional knowledge that was available. Finally, this group was able to define for us what they needed in a reference tool and to help us to make the tools more useful for all orbit determination analysts.

Junior navigators were interviewed to gain insight into how they were learning to use the ODP and what tools would help them to learn more quickly. Through these interviews, we were able to define some of the examples that should be available, such as sample case studies and setup files.

To gain a real understanding of the program, we interviewed both users of the ODP and software developers. In many cases, the developers were able to provide some insight into the iterative nature of the changes in ODP. Users were able to help us to develop the high level and lower level process diagrams of the ODP.

As we interviewed the ODP personnel, we were looking for the actual application of the program suite – how it is used, who uses it, when and in what context specific pieces of the program are invoked. At the same time, however, it was useful for the navigators to provide us with some theoretical background to form a context for the application.

Knowledge Synthesis

Upon completion of the initial knowledge capture phase of the ODP-CBI, the Knowledge Synthesis phase began. It was necessary to determine how best to organize the data to make it accessible to navigators and to make the system extensible, as changes in the program were introduced and as additional knowledge about the ODP was added to the system.

ODP-CBI Overall Organization

As a first step, the high level flow of the ODP process was graphically depicted as the top or entry point into the CBI system. This screen is shown in Fig. 1.

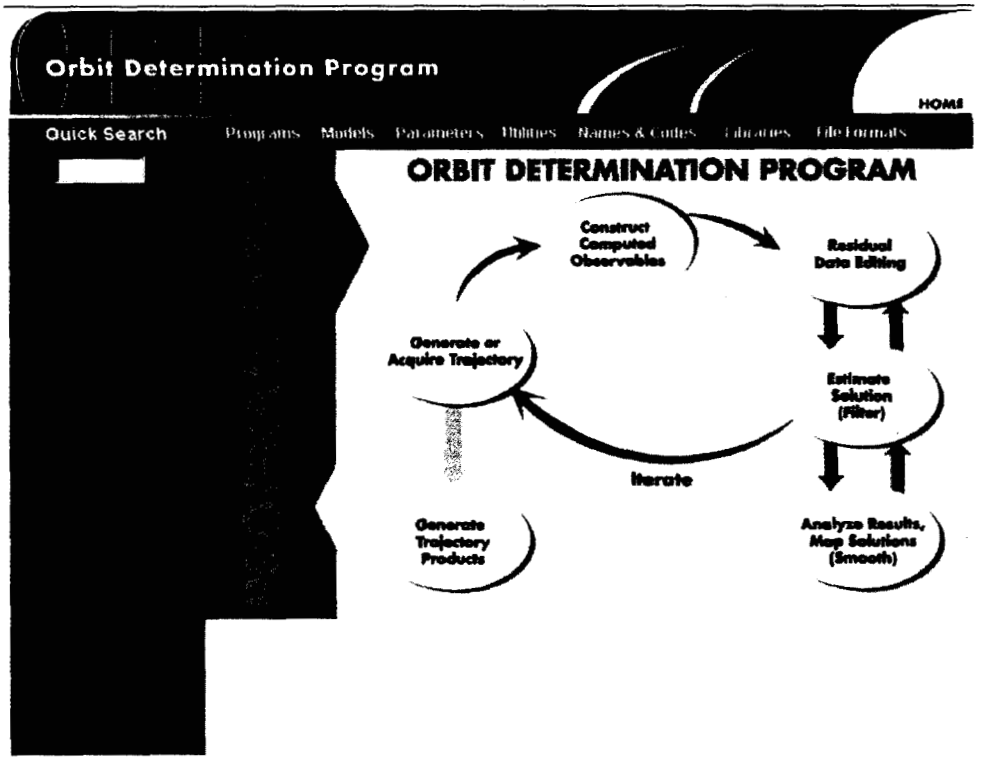

Fig. 1 - High-level Flow of ODP Process

This flow is a clickable map, where each bubble in the flow can be selected individually. The second-level flow is then exposed to the navigator.

Program Setup is a precursor to the orbit determination process and is essential to the successful use of the program. Therefore, it was added to the top-level flow. Selecting the Setup option exposes a variety of information about the pre-execution steps. Included here are incorporated lessons, seminar presentations, and sample files for program setup. Also included are case studies of missions, showing how to run the ODP. This screen is shown in Fig. 2.

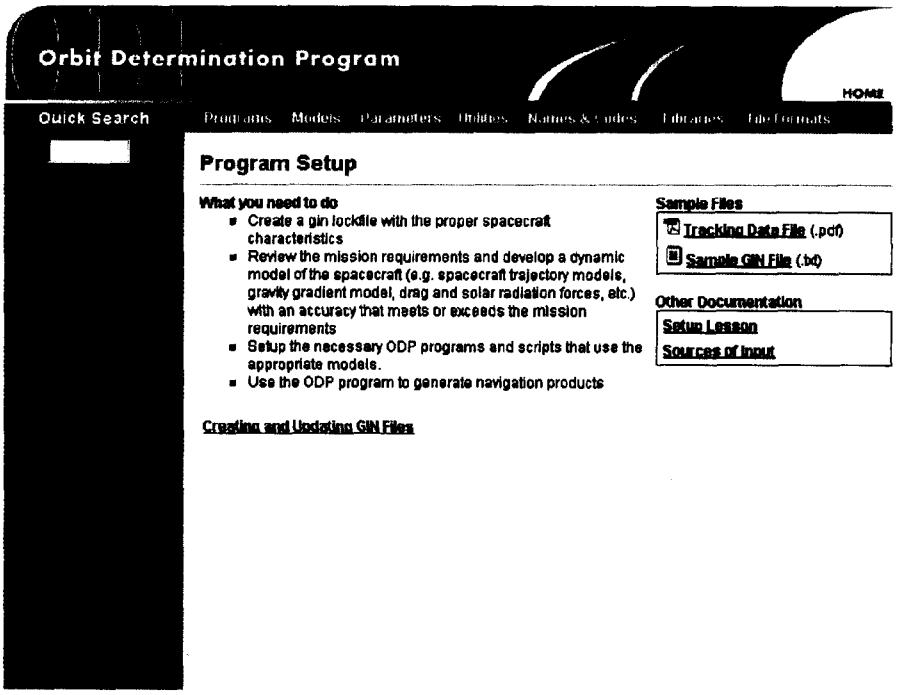

Fig. 2 – Program Setup

Selection of a process on the High-level Flow of ODP Process screen reveals a drill down for detail. This detail includes a process abstract and flow diagram with links to more information. The screen for Generate or Acquire Trajectory is shown in Fig. 3 as a sample.

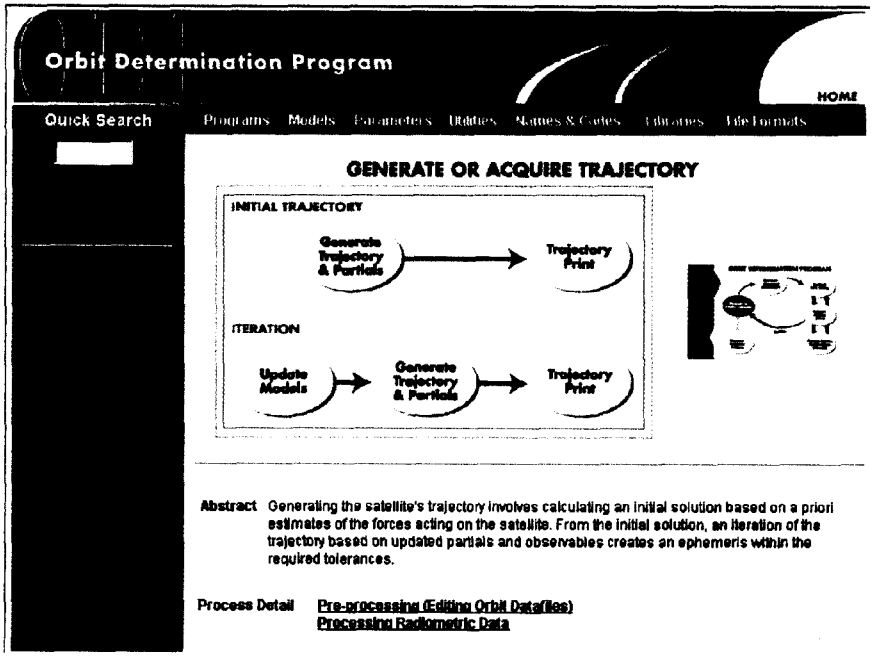

Fig. 3 - Second Level Flow

Incorporation of Tutorials

The eight-week seminar series on Navshell was captured and incorporated into the ODP-CBI. Links within the seminar series documentation include agenda, homework, audio/video screen capture of the demonstrations, and PowerPoint presentations for each of the sessions. Experienced navigators can use the seminar series as refresher information. New navigators can use the series as a beginning training series. By capturing the seminar series, the navigation group was able to reduce the frequency of instructor-led courses for new personnel. This screen is shown in Fig. 4.

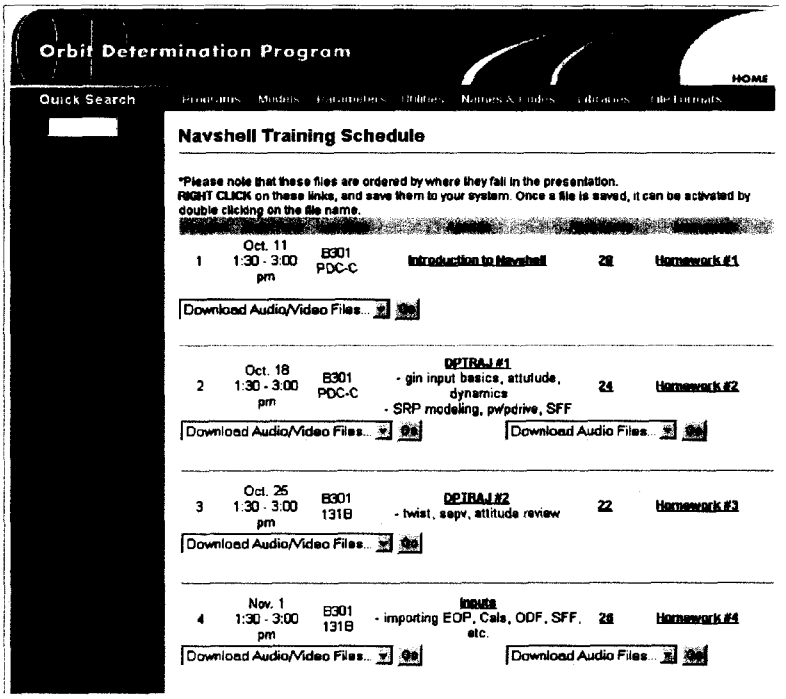

Fig. 4 – Navshell Seminar Series

Knowledge Display

Web-based Instruction

The computer-based instruction program that was developed for the ODP is web-based, reducing the cost of dissemination. Training can now be available on any desktop that includes a standard web browser among its tool set. No additional software (other than free web plug-ins for multi-media display) is necessary, simplifying the distribution of the material, while minimizing capital expenditures, and assuring that the CBI represents the current version of the operational ODP software. Web-based CBI thus makes full use of new technology to enhance the delivery of training services.

Links to Existing Controlled Documentation, Labels and Descriptors – a Database Solution

The database-backed design of the ODP CBI offers the advantage of a cross-referenced and cross-linked display of existing documentation. It thus provides an enhanced documentation set for the experienced navigators. The database design also provides a simple way to organize and extend the document set and immediately integrate new material into the context of the existing material. This feature greatly reduces the possibility that the user will overlook additions to the documentation. Now, through unified search and contextual display, the new material can be displayed alongside the existing information on that topic. An example of this screen is shown in Fig. 5.

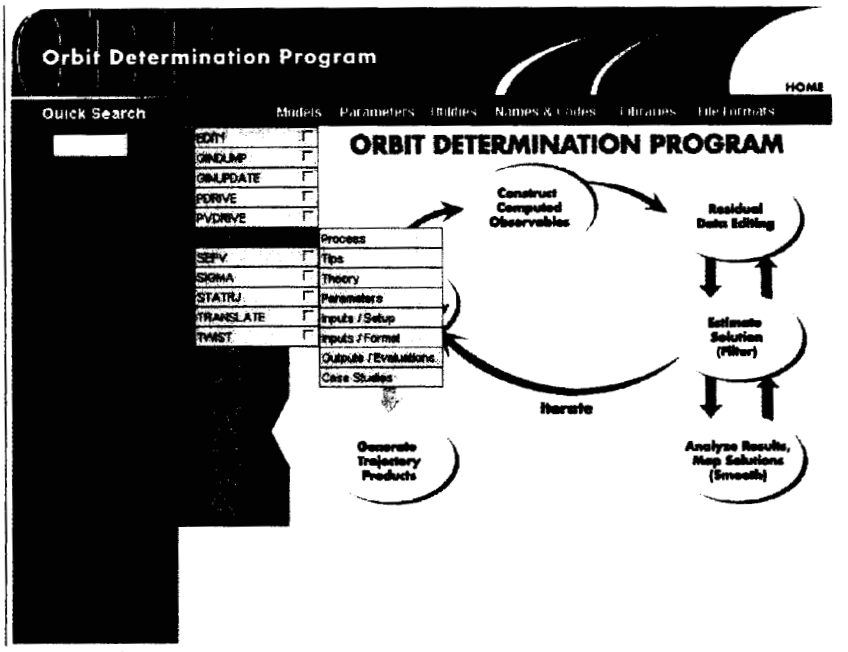

Fig. 5 – Cross-linking and Referencing of ODP Documentation

Descriptive or Narrative Wrapper for Each Model or Process in ODP-Aided Navigation
This feature helps the novice user by providing a description of the function-selected item. Other information places the item in the overall context of the orbit determination process.

Custom Multi-media Elements
Some areas of the ODP are difficult to describe or teach as simple web pages or single images. For these cases, the ODP-CBI tool employs streaming media. This style of presentation is similar to watching a mentor and has the advantage of showing an entire process. Supporting documents reveal links between ODP parameters and the under equations they represent. A typical screen is shown in Fig. 6.

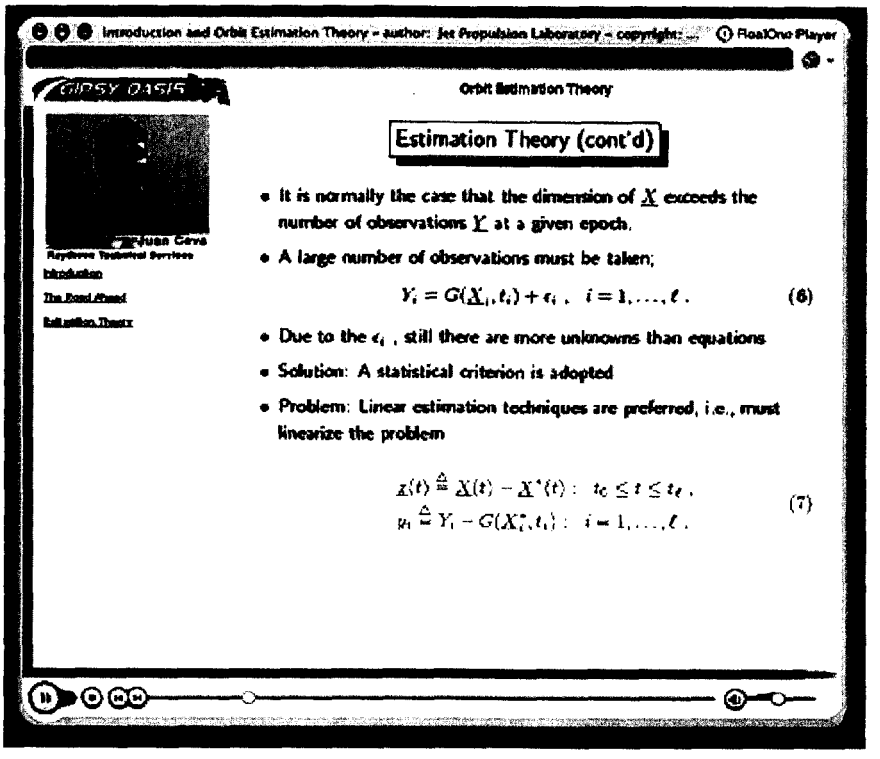

Fig. 6 – Streaming Media Capture of Subject Matter Expert Seminars

This method also shows the proper usage of software with graphical user interfaces. A graphical, interactive navigation data editor can employ lasso grabbing, data deletion, automatic, and interactive re-scaling. Other features include data and case selection and use of colors and symbols to help identify data sources and problems. Streaming media allows a mentor to talk about a process and show the results simultaneously to the student. An example of this screen is shown in Fig. 7.

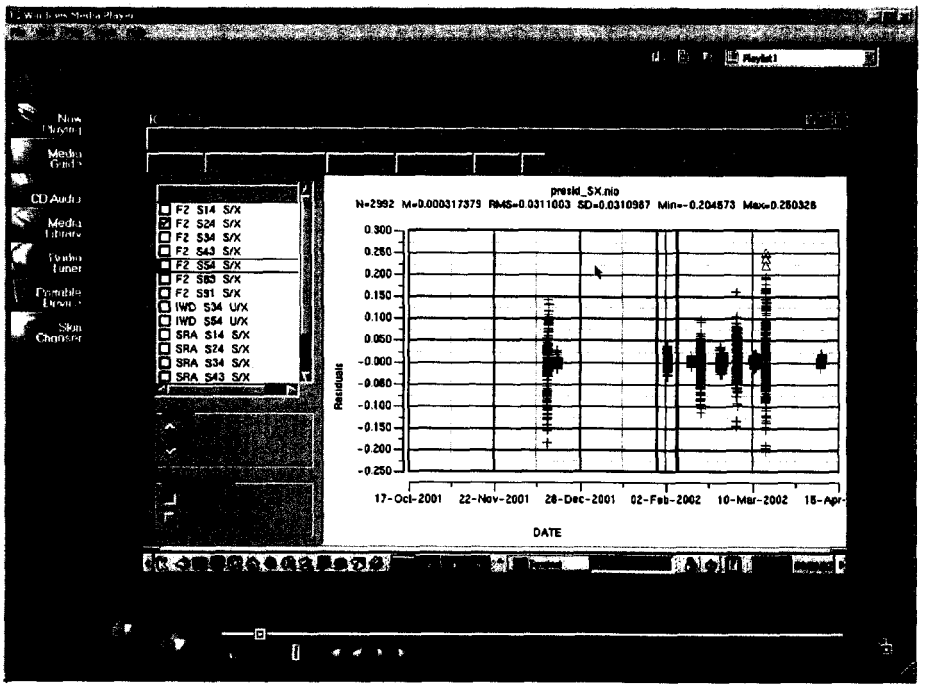

Fig. 7 – Screen-capture of Navshell Seminar Series

Index and Search Capabilities

Search capabilities include a quick search, which produces a comprehensive list of all occurrences of key words. An advanced search capability, as shown in Fig. 8, provides a way for the navigator to select the subset of material that he or she wants to view. For instance, the key word search may be limited to the program descriptions containing that word, providing a more focused approach to data mining. Once a search result is selected, the cross-links are then exposed for the navigator. These might include parameters, utilities and models that are also associated with that key word.

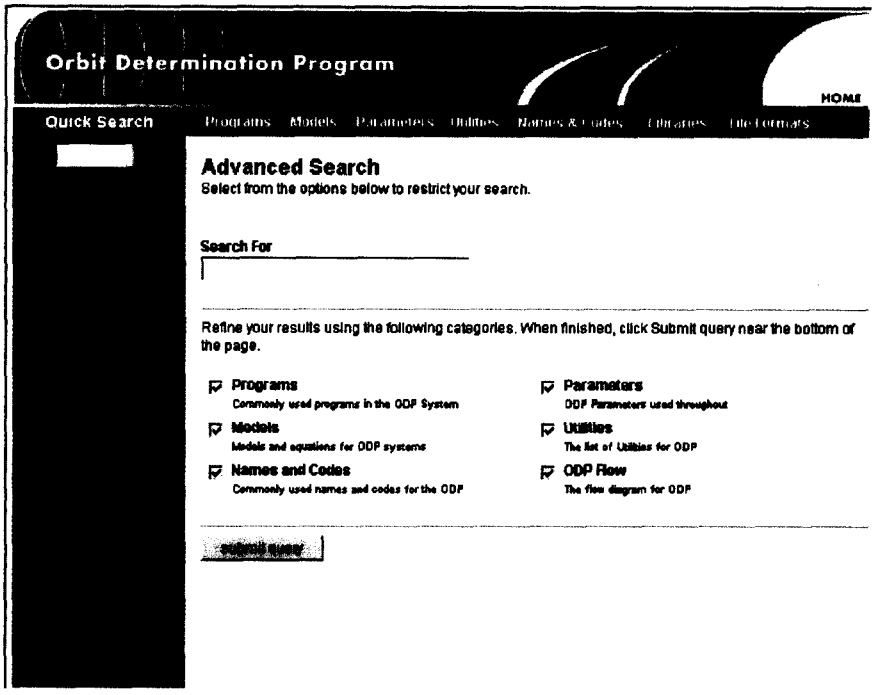

Fig. 8 – Advanced Search Capabilities

Selected Working Examples, Case Studies, and Exercises

Case studies of representative missions were included as linked documents within the ODP-CBI tools. It is intended that these case studies will be further cross-linked to specific processes to demonstrate how the ODP is applied in a practical example.

Tips, Tricks and Frequently Asked Questions (FAQs)

Built into the ODP-CBI tool is the ability to capture expert knowledge as "Tips" in the context of the ODP – for example, associated with a particular program or model or parameter. These tips are entered into a database and referenced in the context of their topic and category. They are also exposed at the top level on a categorized list. The ability to capture expert knowledge and instantly expose it to the user community is an example of the use of technology to provide innovative training tools. In this case, the tips can supplement the mentor relationship and extend it beyond the one-on-one training that is the usual scenario. This information enables the novice and senior engineer to troubleshoot a problem and de-mystify the common pitfalls of orbit determination. This screen is shown in Fig. 9.

The instructional tool provides a set of guidelines[13] for doing orbit determination as shown in Fig. 9. Each guideline is a link to more detailed information.

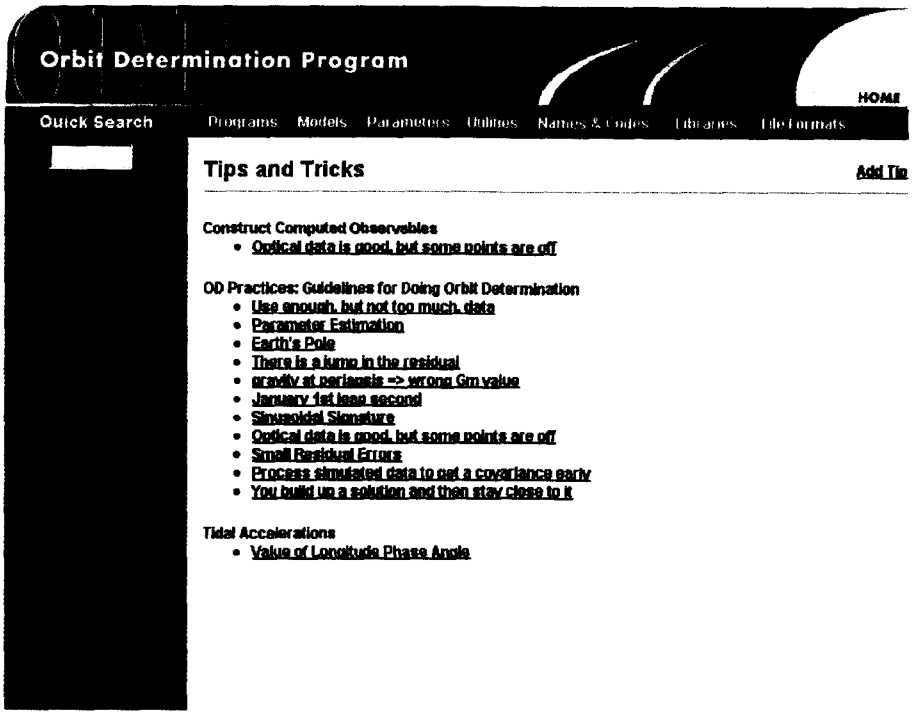

Fig. 9 – Tips, Tricks and FAQs

Verification of Knowledge System and Content

Review of CBI System and Materials by Navigation Experts
Cognizant programmers have reviewed the file formats and parameter descriptions. The changes that are identified in this process are being implemented as part of the ongoing maintenance phase.

Feedback from Experts and from Users New to the ODP
A formal mechanism to capture feedback from users was incorporated into the ODP CBI. This feedback is directed to the developers for bug fixes and for program enhancement. Such feedback can be supplied via user-initiated pop-up as shown in Fig. 10 or Bugzilla[14], a formal anomaly reporting system.

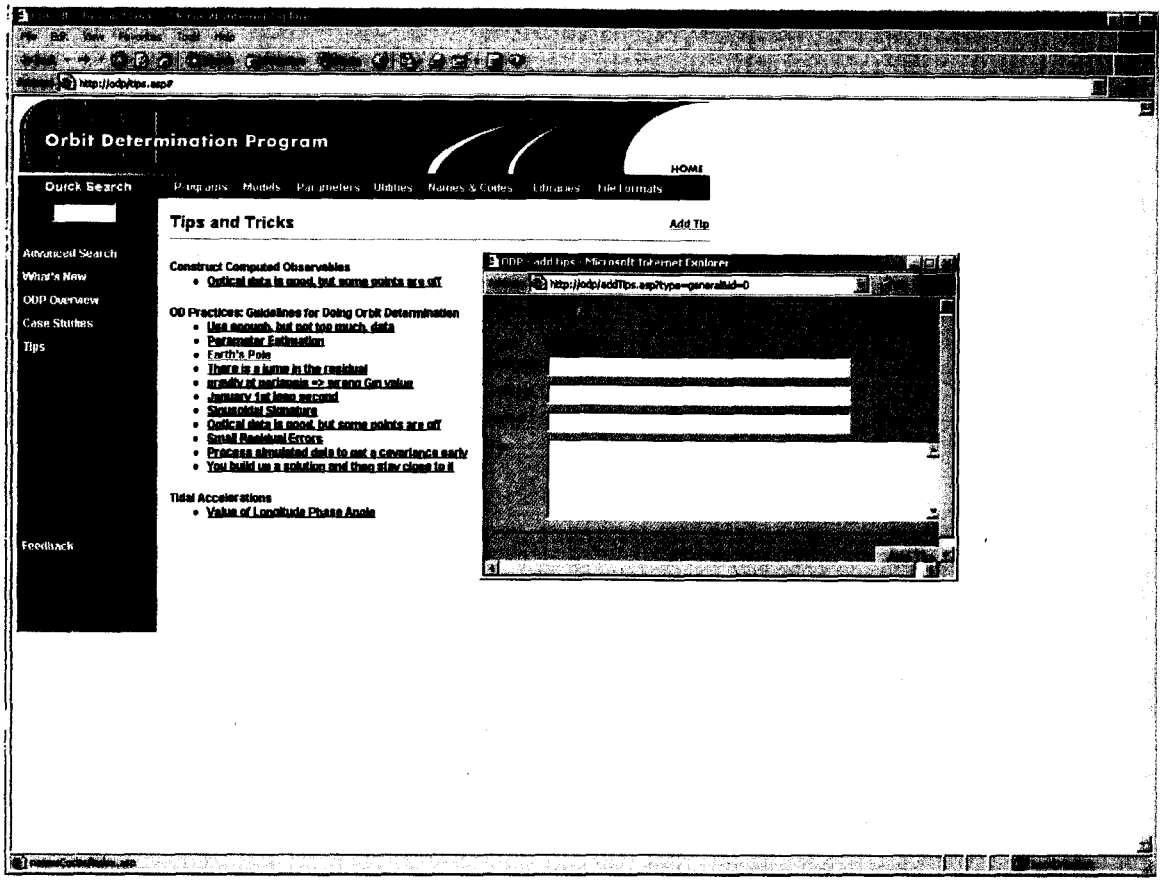

Fig. 10 – Capturing Subject Matter Expert Advice within the Context of the ODP Process

3. LESSONS LEARNED

The lessons learned to date are:

(a) Learning how to run the ODP is not the same as learning how to steer an antenna. One attempt to develop a CBI tool followed the approach that training could be accomplished as one describes the well-defined, step-by-step operation of steering an antenna. However, this approach was soon abandoned because it is ineffective for the problem of selecting the optimal strategy for doing orbit determination. For example, Reference 2 considers several OD strategies that were employed for the Mars Odyssey spacecraft.

(b) Developing a CBI system for a complex subject is an iterative process that requires frequent reviews of progress and design decisions.

(c) Collecting, structuring and distributing the history of knowledge gained over the last 40 years is a formidable task. It requires a variety of methods and a great deal of patience and persistence.

4. CONCLUDING REMARKS

Tasks the Analyst Can Attack Using This Tool
The beginning analyst will use this tool to learn the step-by-step procedure for running the ODP. In this learning process, the analyst will be aided by the working examples of process flow and input and output, the tutorials (e.g., the set of Navshell tutorials), and the information provided about the program at varying depths of viewing.

The experienced analyst will use this tool to answer specific questions concerning individual parameters, parameter types and defaults, array sizes and syntax. One can then follow readily accessible links to find related parameters and investigate their interactions.

Both the beginner and the expert analysts will seek the answer to a myriad of specific questions such as:

How does one model the physical spacecraft structure?
How does one build a solar pressure model?
How does one deal with small forces?
How does one iterate on stochastic parameters?
How does one process differenced Doppler data?
What is a B-Plane?

All users will also benefit from the tips and tricks reference. This feature provides general ground rules, and common pitfalls, mistakes and errors. Also available are links to a database containing translations of error messages and error numbers. This information, accessible via index and search capabilities, will help to de-mystify the OD process.

Results
The CBI tool has been described as a "mature product." It has been released for use by JPL personnel for pre-flight analyses and operational activities. Metrics will measure its effectiveness in meeting the requirements listed in Section 1. Maintenance in response to user comments and suggestions is continuing.

Future Enhancements
The current version of the CBI tool considers range and Doppler data. Possible future enhancements would be to add the processing of other data types such as delta-DOR (differenced differential one-way range), launch angles, and optical navigation measurements. Additional functionality may include a method for monitoring and approving user tips, web-based access to update content as required, parsing of additional case studies within the tool, and expansion of the tool to include new software developments.

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COMPUTER-BASED INSTRUCTION AND REFERENCE DOCUMENTATION SYSTEM FOR THE ORBIT DETERMINATION PROGRAM

Gerald R. HINTZ
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099

Mark Ryne[1], Michael Watkins[1], Maureen Kenney[2], David Overoye[2]
[1]Jet Propulsion Laboratory, California Institute of Technology
[2]Raytheon, Pasadena, California

ABSTRACT *- The Orbit Determination Program set has been used at the Jet Propulsion Laboratory for nearly half a century to enable precision navigation of interplanetary and earth-orbiting missions and to support a myriad of scientific investigations. Executing this software package successfully is a challenging task for experienced personnel and a daunting one for junior navigators. The effort described in this paper provides a computer-based, web-enabled instructional and reference tool to aid both experienced and beginning personnel in the art of performing orbit determination with this software.*

KEYWORDS: navigation, orbit determination, computer-based instruction, web-enabled instruction

INTRODUCTION

The Orbit Determination Program (ODP) has been developed over a period of 40 years. This software set has enabled accurate navigation[1,2] of NASA's planetary exploration missions to explore every planet in the solar system (except Pluto) and many of their natural satellites, the sun, comets Halley, Giacobini-Zinner and Borrelly, and asteroids Ida, Gaspra, Mathilde, Eros, Annefrank, and Braille. This software set has provided the navigation function for more than 150 missions, including Mariners 2, 4-7, 9-10, Rangers 5, 7-9, Surveyors 1, 3, 5-7, Lunar Orbiters 1-5, Pioneers 6-13, Vikings 1-2, Voyagers 1-2, ISEE-3, Vegas 1-2, Sakigake, Giotto, Suisei, Magellan, Galileo, HITEN, Hubble, Ulysses, TOPEX/Poseidon, Mars Observer, NEAR, Mars Pathfinder, Space VLBI (VSOP), Mars Global Surveyor, Cassini-Huygens, Lunar Prospector, Deep Space 1, Mars Climate Orbiter, Mars Polar Lander/Deep Space 2, Stardust, Shuttle Radar Topography Mission (SRTM), 2001 Mars Odyssey, Genesis, Gravity Recovery and Climate Experiment (GRACE), Space Infrared Telescope (SIRTF), and Mars Exploration Rovers 1-2, plus NIMBUS 7, LAGEOS 2, ROSAT, AMPTE-IRM, AMPTE-CCE, PHOBOS 1-2, GEOTAIL, Clementine, and the Space Flyer Unit (SFU). Hence, this software has supported national and international missions for the Jet Propulsion Laboratory (JPL), Langley Research Center, Ames, Goddard Space Flight Center, the European Space Agency (ESA), the German Space Operations Center (GSOC), Applied Physics Laboratory (APL), the Space Research Institute (IKI), the National Space Development Agency of Japan (NASDA), The Institute of Space and Astronomical Science (ISAS), and the National Research Laboratory (NRL).

The ODP software has also supported significant scientific investigations in celestial mechanics, relativity, geodesy, ephemerides, and celestial reference frames. Many of the scientific discoveries of NASA's planetary exploration program have been dependent on accurate navigation provided through use of this software. Some examples of the discoveries made possible by using this software include determining high order gravity fields for Venus[3], Mars[4], the earth, and the moon[5], near real-time gravity modeling of the asteroid Eros[6], lunar mascons from Lunar Orbiter V data[7], topographical features[8] of Venus and Mars, planetary rotation periods[3,9,10], planetary and satellite mass determinations[3,4,5], atmospheric structure for Venus and Mars, relativity model confirmation, geophysical parameters determination[6,9], and geodesy in general for the planets[9,10,11]. The ODP has also been used to make corrections to the planetary and natural satellite ephemerides.

The software set, including the trajectory modeling and propagation programs (DPTRAJ for Double Precision Trajectory) and the orbit estimation and prediction set (ODP for Orbit Determination Program), consists of 2.0 million lines of code with 16 major programs, 350,000 input parameters, 151 utility programs, 55 libraries, 196 scripts, and 7516 files. Performing the various tasks that are a part of the orbit determination effort involves executing selected subsets of this system. Hence, running this software package is a challenging task for experienced personnel and a daunting one for junior navigators.

This paper describes an effort to provide an instructional and reference tool utilizing web-based technology to minimize the time and financial costs involved in training both experienced and beginning personnel in the art of performing orbit determination with this software. The paper includes the list of requirements and goals of the computer-based instructional (CBI) tool, its development, its use, and the lessons learned to date.

1. REQUIREMENTS AND GOALS FOR THE COMPUTER-BASED INSTRUCTIONAL SYSTEM

The need for the instructional tool was driven by several factors, including the increasing complexity of orbit determination (OD) with the ever present need to avoid operational risk and to contain costs. Another factor was the institutional change from supporting a small number of large flight missions with large navigation teams to supporting a large number of small missions with small navigation teams. The driving requirements of the development effort were to:

(a) Reduce dependence on experienced personnel for provision of training activities. New navigators traditionally acquire experience and instruction with the ODP through a mentoring process, which has proven to be successful. However, mentoring new personnel, while a critical function, is also time-consuming. Therefore, it is important to develop tools to aid this task.

(b) Capture and manage knowledge. As senior personnel retire from active participation in the field, it becomes imperative to capture the accomplishments and experience of the first generation of interplanetary navigators to provide a guide for their replacements.

(c) Reduce the time required to train a new navigator for flight operations. In the past, the training period for a new employee could extend to a year or beyond. It is essential, in this era of many small missions, that the training be accomplished more quickly than in the past.

(d) Reduce training costs. Training applies to all personnel, since it must include the full-scale training of an inexperienced person as well as provide the occasional reference or refresher required by experienced navigators. Providing separate training for these two groups is expensive to develop, maintain, and update. Thus, one goal of the computer-based instruction (CBI) was that it provide for the needs of both groups.

(e) Manage risk. It is necessary to reduce risks from operational errors. Standardizing the training material in order to provide a common reference for all navigators is a key element in risk reduction in a multimission environment.

(f) Provide a tool that is flexible enough to cope with the constantly changing spacecraft, missions and associated parameters. Orbit determination software evolves to meet the requirements specified by each mission and changing spacecraft parameters throughout each mission.

(g) Provide a system that is easily maintained and updated under configuration control with efficient and secure accessibility.

Additional design goals were also considered as follows:

(a) The ideal CBI system would make it possible for personnel to move from project to project seamlessly.

(b) A system that could easily and efficiently be applied to the next generation of orbit determination software would preserve the capital investment in the program and infrastructure.

(c) The training tool would serve as a vehicle for introducing Navshell, an ODP execution processor. Navshell allows standardized inputs for multiple missions with diverse requirements and supports a uniform interface for numerous operational scenarios such as a single batch sequential filter, a multi-batch stochastic filter, and differential and optical data types. This flexible tool can provide standardized scripts for novice users or production runs while retaining the ability to use the most advanced and generalized capabilities of the software suite.

To meet these requirements and goals, it was determined to be necessary to provide both an instructional "how to" tool for new navigators and a reference system for experts. It was also ascertained that another characteristic of the system is that it must emphasize the application of the orbit determination process. This tool was not to be a comprehensive description of underlying principles of physics or mathematical formulations, but rather a "how to" guide.

2. DEVELOPMENT OF THE COMPUTER-BASED INSTRUCTIONAL SYSTEM

Knowledge Capture

Inherited Training Tools and Materials

The documentation for the ODP consisted of four very large manuals, sectioned by areas such as Programs, Utilities, and Parameters, without cross-linking between volumes or sections. These manuals had been converted to static HTML and were available online. An institutional search would point to pages containing similar material, but such a search was not streamlined. Additional documentation was added over the years. This information often took the form of a What's New web page that included a list of changes, additions and corrections relative to the original documentation. Manual pages were available for new utilities within the directories where those utilities were stored.

Other input included institutional spacecraft navigation procedures and operational procedures developed for navigating the Cassini spacecraft, including those for updating media calibration files, iterating runs to obtain a converged solution, generating B-plane plots, updating tracking data logs, creating stochastic or residual plots, and creating a summary print.

Orbit Determination Workshop

An orbit determination workshop was conducted as the first step in developing a CBI tool. This workshop, spread over one week, helped the CBI developers understand the ODP and the inherited documents. One presentation entitled, "Using the ODP for Pre-Flight Analysis and Cruise OD," provided an overview ~~as follows.~~

~~Spacecraft navigation can be separated into three distinct tasks:~~, covered the following tasks:

1. Obtaining observation data.
2. Updating the spacecraft state and its predicted trajectory, using the observations in task 1.
3. Comparing the predicted trajectory outcome in task 2 and the desired target and computing a trajectory correction maneuver, if necessary.

~~Task 1 is performed in two basic modes. The first mode is radiometric tracking, which uses radio signals sent to and received from the spacecraft (or sometimes only a signal from the spacecraft, i.e., one-way data) to measure the radial distance or velocity of the spacecraft (ranging and Doppler). The second mode represents measurement techniques that determine the spacecraft's position in the plane-of-sky, i.e., orthogonal to radiometric tracking. One of these mode 2 techniques is optical navigation, in which the spacecraft makes images of background stars and its target body, through the use of on-board cameras. Another mode 2 technique is Very Long Baseline Interferometry, which combines a signal from a quasar with a signal from the spacecraft. Mode 2 techniques are not discussed in this presentation.~~

~~Task 2 is orbit determination (OD). The particular OD practiced at JPL for interplanetary missions is a differential correction method (as opposed to Gaussian or Laplacian methods). Differential~~

~~correction is suitable to processes with continuous (or nearly continuous) observations because the difference between the observations and the predicted measurements can be computed, and any difference subsequently used to correct previous assumptions of the spacecraft's baseline or reference trajectory. In this process, the residual, the observed minus the computed (O – C) values of the observation data parameters, is reduced to random errors about zero by iteratively updating the reference trajectory by linear corrections[12].~~

~~In task 3, flight path control adjusts the trajectory according to the best OD information available from task 2.~~

This presentation also considered these three navigation tasks in more detail, including the process of obtaining radiometric range and Doppler data from the Deep Space Network (DSN), ephemeris generation, calibration of media and platform parameters, the parameter estimation of a spacecraft state[12], the mapping of the navigation errors to the target B-plane, and OD covariance analyses. The last of these tasks may be performed years before launch to judge the feasibility and limitations of a particular baseline trajectory.

Another presentation, "SIGMA: The Filter and Mapping Module of the ODP," included the mathematical fundamentals of this software routine. "Trajectory Integration" covered integration control, gravity modeling and perturbing accelerations, and the generation of partial derivatives of the spacecraft state with respect to requested parameters. The last presentation, "Making a Usable ODP System," discussed the ODP heritage, main programs, input, file types, and the use of the Navshell script to make multiple program runs automatically, handle file input/output connections, catch input errors before execution, detect execution failures, and catalog results.

Interviews

It was determined that interviewing the navigators was a necessary way to understand the ODP. Group meetings were considered and rejected because each navigator had developed a separate method for using the ODP. A group meeting would require a lengthy discussion of each of these techniques, rather than a more general discussion of the common process flow of the ODP. Interviews began with the Navigation management staff, proceeded to senior navigators, and concluded with a series of interviews of junior navigators and program developers.

The managers and senior navigators provided several elements to the ODP-CBI development process. They were able to articulate how they use the ODP to perform navigational tasks, thus helping to define the ODP processes. The senior level personnel were also helpful in defining how they mentor new employees – what they tell the junior navigators and how they elaborate on the documentation. This information in turn led to the development of our knowledge capture tools, as we began to understand the scope of the institutional knowledge that was available. Finally, this group was able to define for us what they needed in a reference tool and to help us to make the tools more useful for all orbit determination analysts.

Junior navigators were interviewed to gain insight into how they were learning to use the ODP and what tools would help them to learn more quickly. Through these interviews, we were able to define some of the examples that should be available, such as sample case studies and setup files.

To gain a real understanding of the program, we interviewed both users of the ODP and software developers. In many cases, the developers were able to provide some insight into the iterative nature of the changes in ODP. Users were able to help us to develop the high level and lower level process diagrams of the ODP.

As we interviewed the ODP personnel, we were looking for the actual application of the program suite – how it is used, who uses it, when and in what context specific pieces of the program are invoked. At the same time, however, it was useful for the navigators to provide us with some theoretical background to form a context for the application.

Knowledge Synthesis

Upon completion of the initial knowledge capture phase of the ODP-CBI, the Knowledge Synthesis phase began. It was necessary to determine how best to organize the data to make it accessible to

navigators, and to make the system extensible, as changes in the program were introduced, and as additional knowledge about the ODP was added to the system.

ODP-CBI Overall Organization

As a first step, the high level flow of the ODP process was graphically depicted as the top or entry point into the CBI system. This screen is shown in Fig. 1.

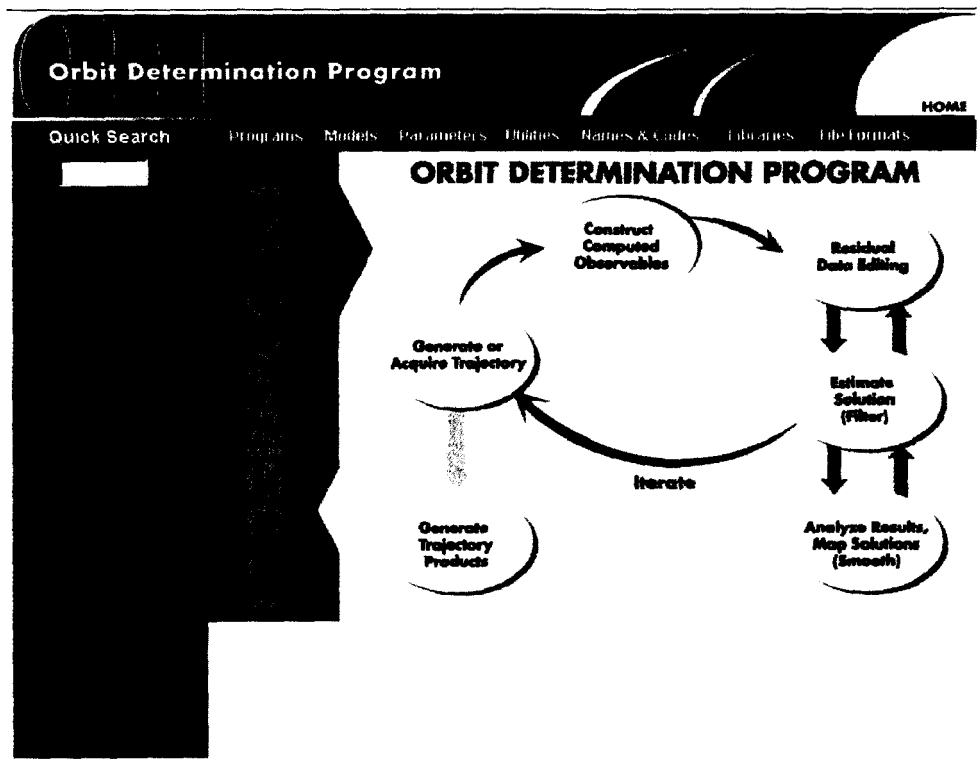

Fig. 1 - High-level Flow of ODP Process

This flow is a clickable map, where each bubble in the flow can be selected individually. The second-level flow is then exposed to the navigator.

Program Setup is a precursor to the orbit determination process and is essential to the successful use of the program. Therefore, it was added to the top-level flow. Selecting the Setup option exposes a variety of information about the pre-execution steps. Included here are incorporated lessons, seminar presentations, and sample files for program setup. Also included are case studies of missions, showing how to run the ODP. This screen is shown in Fig. 2.

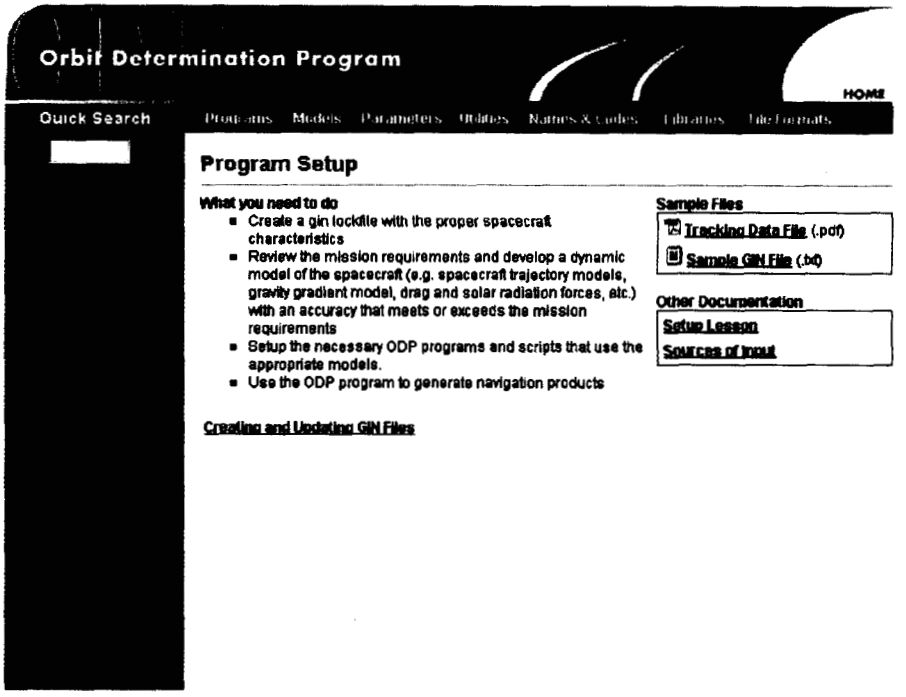

Fig. 2 – Program Setup

Selection of a process on the High-level Flow of ODP Process screen reveals a drill down for detail. This detail includes a process abstract and flow diagram with links to more information. The ~~This~~ screen for Generate or Acquire Trajectory is shown in Fig. 3 as a sample.

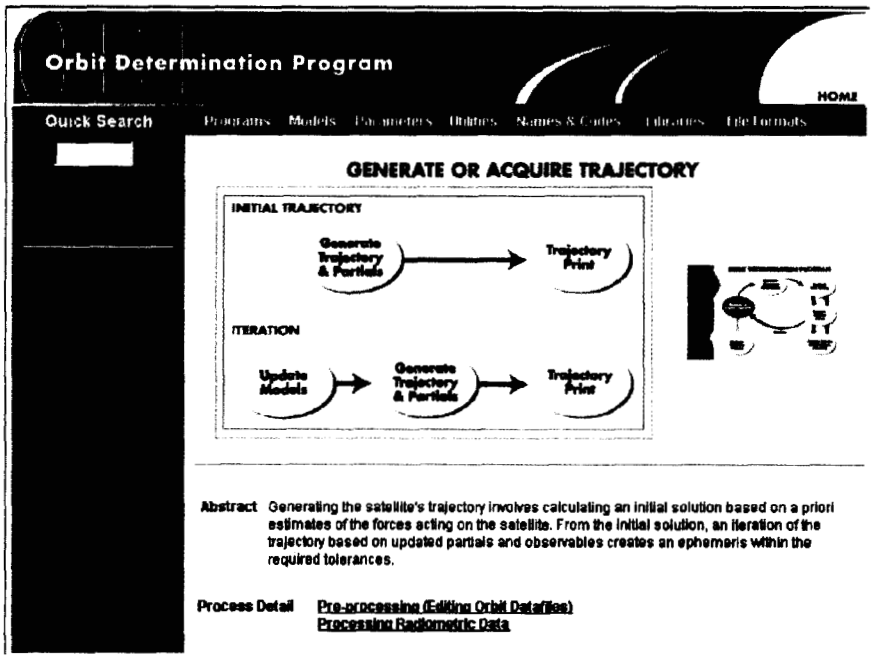

Fig. 3 - Second Level Flow

Incorporation of Tutorials

The eight-week seminar series on Navshell was captured and incorporated into the ODP-CBI. Links within the seminar series documentation include agenda, homework, audio/video screen capture of the demonstrations, and PowerPoint presentations for each of the sessions. Experienced navigators can use the seminar series as refresher information. New navigators can use the series as a beginning training series. By capturing the seminar series, the navigation group was able to reduce the frequency of instructor-led courses for new personnel. This screen is shown in Fig. 4.

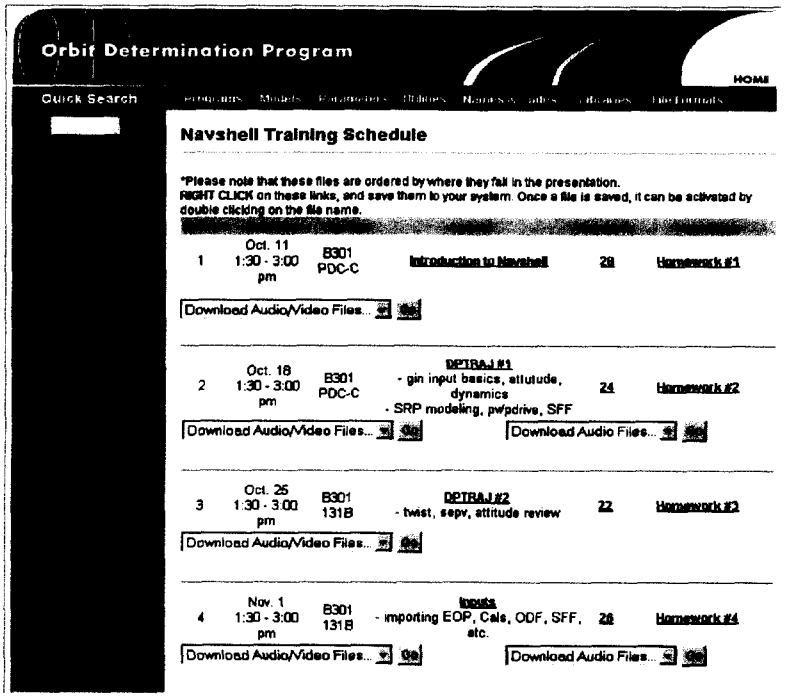

Fig. 4 – Navshell Seminar Series

Knowledge Display

Web-based Instruction

The computer-based instruction program that was developed for the ODP is web-based, reducing the cost of dissemination. Training can now be available on any desktop that includes a standard web browser among its tool set. No additional software (other than free web plug-ins for multi-media display) is necessary, simplifying the distribution of the material, while minimizing capital expenditures, and assuring that the CBI represents the current version of the operational ODP software. Web-based CBI thus makes full use of new technology to enhance the delivery of training services.

Links to Existing Controlled Documentation, Labels and Descriptors – a Database Solution

The database-backed design of the ODP CBI offers the advantage of a cross-referenced and cross-linked display of existing documentation. It thus provides an enhanced documentation set for the experienced navigators. The database design also provides a simple way to organize and extend the document set and immediately integrate new material into the context of the existing material. This feature greatly reduces the possibility that the user will overlook additions to the documentation. Now, through unified search and contextual display, the new material can be displayed alongside the existing information on that topic. An example of this screen is shown in Fig. 5.

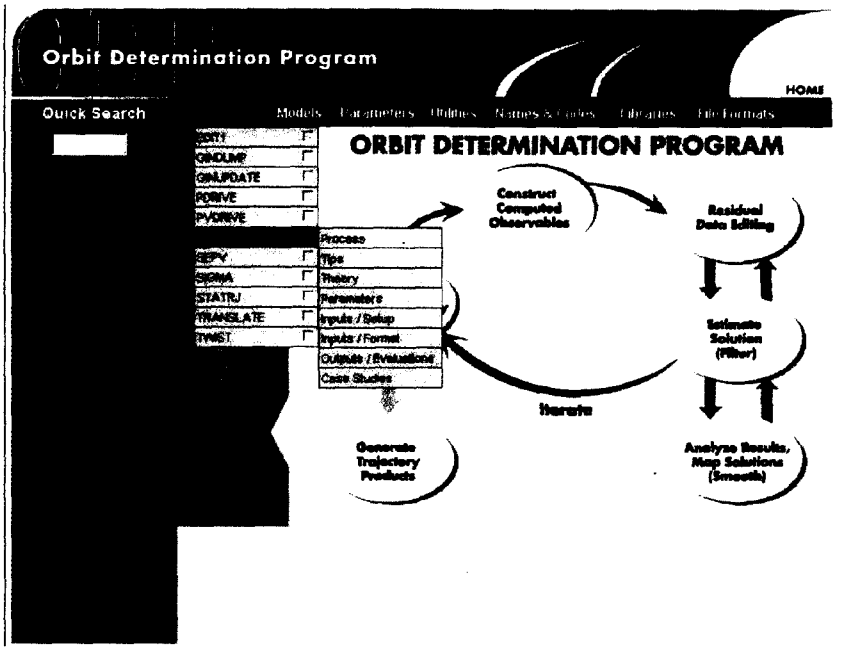

Fig. 5 – Cross-linking and Referencing of ODP Documentation

Descriptive or Narrative Wrapper for Each Model or Process in ODP-Aided Navigation
This feature helps the novice user by providing a description of the function-selected item. Other information places the item in the overall context of the orbit determination process.

Custom Multi-media Elements
Some areas of the ODP are difficult to describe or teach as simple web pages or single images. For these cases, the ODP-CBI tool employs streaming media. This style of presentation is similar to watching a mentor and has the advantage of showing an entire process. Supporting documents reveal links between ODP parameters and the under equations they represent. A typical screen is shown in Fig. 6.

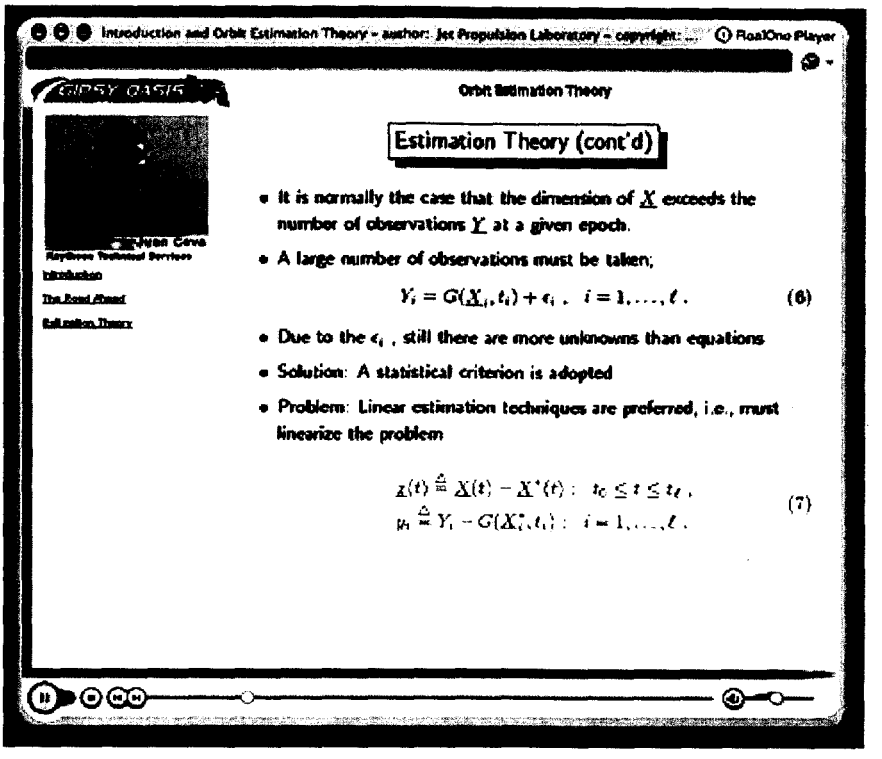

Fig. 6 – Streaming Media Capture of Subject Matter Expert Seminars

This method also shows the proper usage of software with graphical user interfaces. A graphical, interactive navigation data editor can employ lasso grabbing, data deletion, automatic, and interactive re-scaling. Other features include data and case selection and use of colors and symbols to help identify data sources and problems. Streaming media allows a mentor to talk about a process and show the results simultaneously to the student. An example of this screen is shown in Fig. 7.

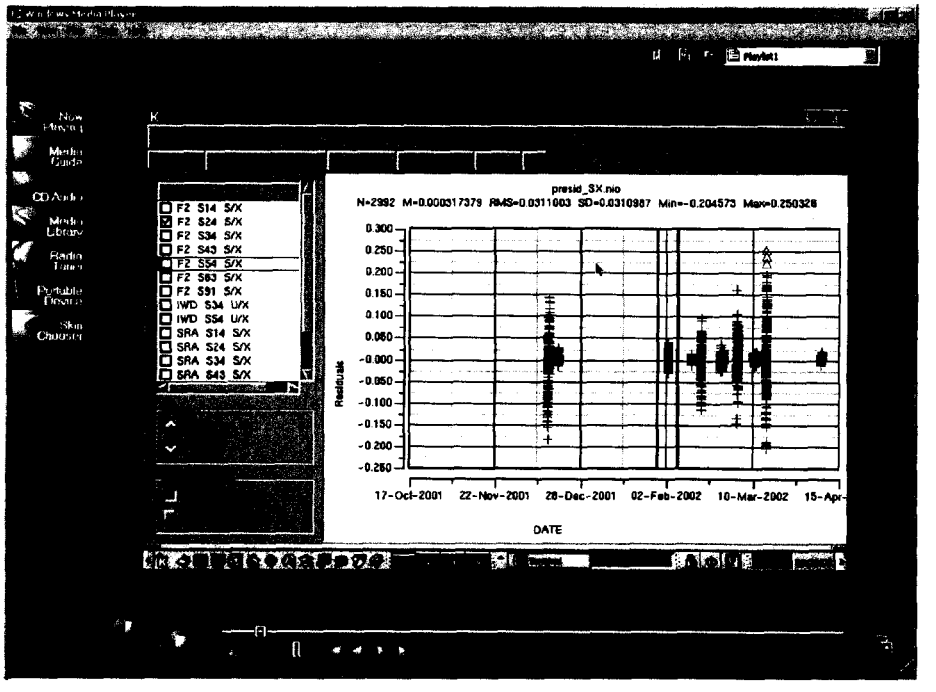

Fig. 7 – Screen-capture of Navshell Seminar Series

Index and Search Capabilities

Search capabilities include a quick search, which produces a comprehensive list of all occurrences of key words. An advanced search capability, as shown in Fig. 8, provides a way for the navigator to select the subset of material that he or she wants to view. For instance, the key word search may be limited to the program descriptions containing that word, providing a more focused approach to data mining. Once a search result is selected, the cross-links are then exposed for the navigator. These might include parameters, utilities and models that are also associated with that key word.

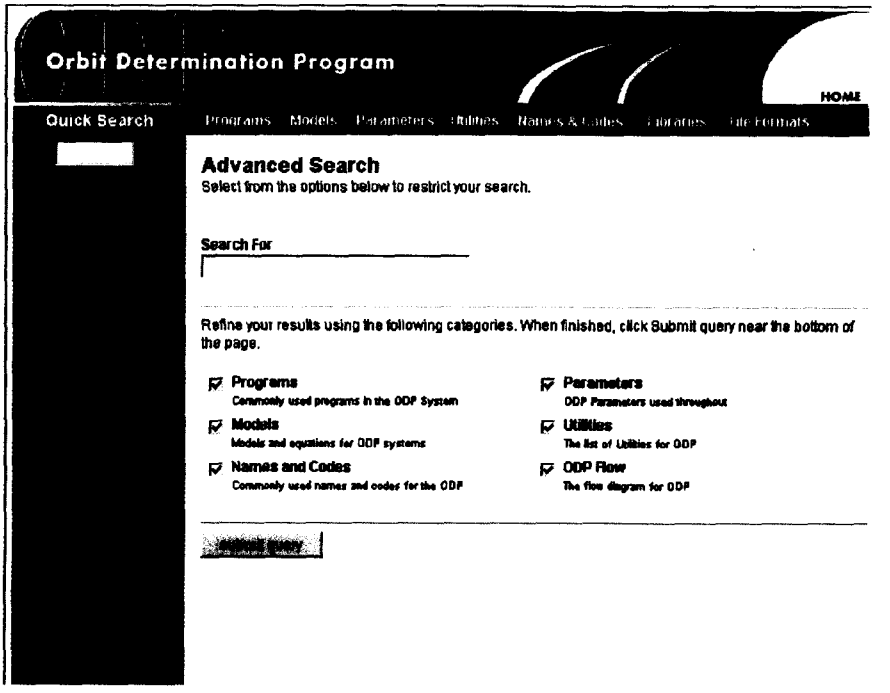

Fig. 8 – Advanced Search Capabilities

Selected Working Examples, Case Studies, and Exercises

Case studies of representative missions were included as linked documents within the ODP-CBI tools. It is intended that these case studies will be further cross-linked to specific processes to demonstrate how the ODP is applied in a practical example.

Tips, Tricks and Frequently Asked Questions (FAQs)

Built into the ODP-CBI tool is the ability to capture expert knowledge as "Tips" in the context of the ODP – for example, associated with a particular program or model or parameter. These tips are entered into a database and referenced in the context of their topic and category. They are also exposed at the top level on a categorized list. The ability to capture expert knowledge and instantly expose it to the user community is an example of the use of technology to provide innovative training tools. In this case, the tips can supplement the mentor relationship and extend it beyond the one-on-one training that is the usual scenario. This information enables the novice and senior

engineer to troubleshoot a problem and de-mystify the common pitfalls of orbit determination. This screen is shown in Fig. 9.

The instructional tool provides a set of guidelines[13] for doing orbit determination as shown in Fig. 9. Each guideline is a link to more detailed information.

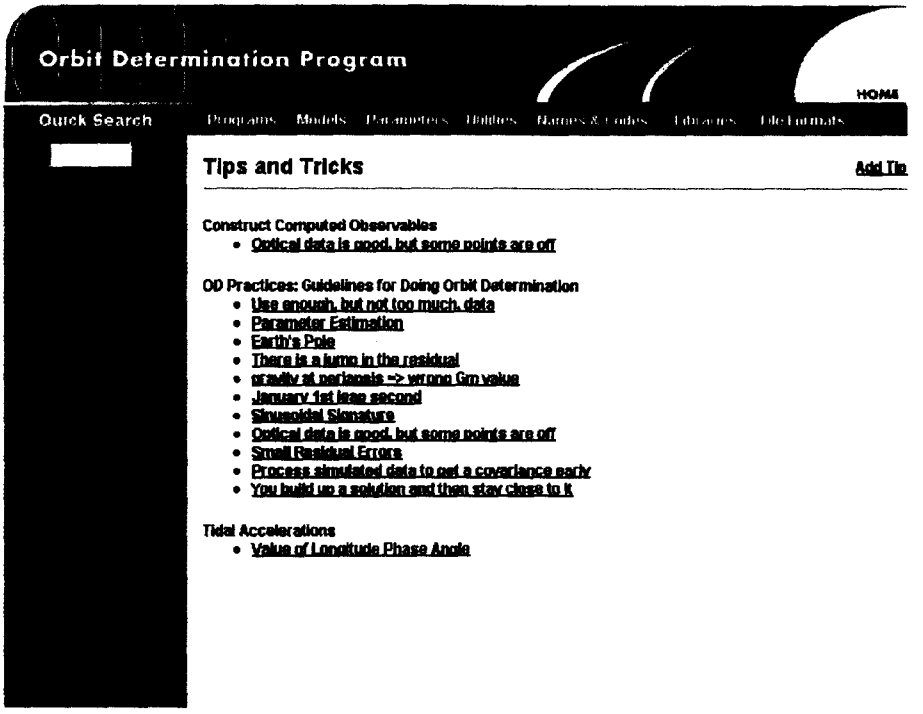

Fig. 9 – Tips, Tricks and FAQs

Verification of Knowledge System and Content

Review of CBI System and Materials by Navigation Experts
Cognizant programmers have reviewed the file formats and parameter descriptions. The changes that are identified in this process are being implemented as part of the ongoing maintenance phase.

Feedback from Experts and from Users New to the ODP
A formal mechanism to capture feedback from users was incorporated into the ODP CBI. This feedback is directed to the developers for bug fixes and for program enhancement. Such feedback can be supplied via user-initiated pop-up as shown in Fig. 10 or Bugzilla[14], a formal anomaly reporting system.

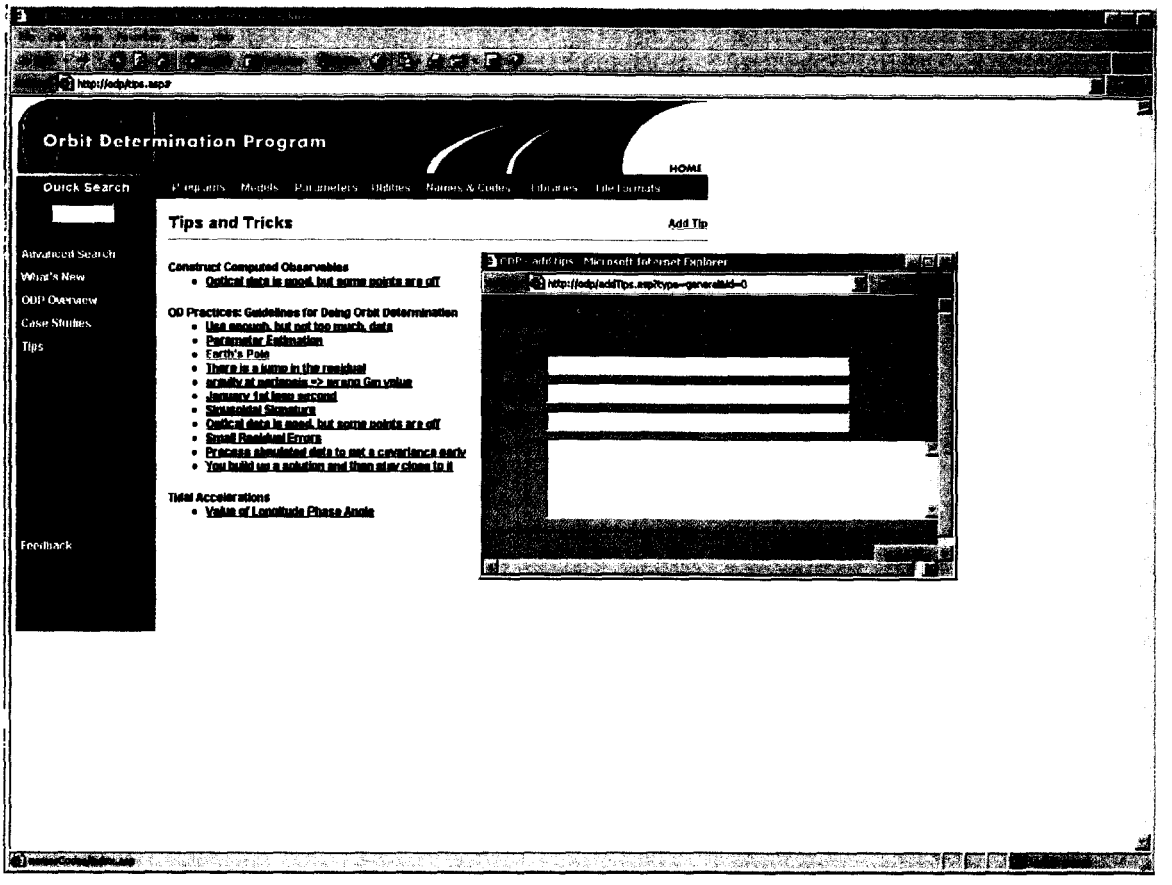

Fig. 10 – Capturing Subject Matter Expert Advice within the Context of the ODP Process

3. LESSONS LEARNED

The lessons learned to date are:

(a) Learning how to run the ODP is not the same as learning how to steer an antenna. One attempt to develop a CBI tool followed the approach that training could be accomplished as one describes the well-defined, step-by-step operation of steering an antenna. However, this approach was soon abandoned because it is ineffective for the problem of selecting the optimal strategy for doing orbit determination. For example, Reference 2 considers several OD strategies that were employed for the Mars Odyssey spacecraft.

(b) Developing a CBI system for a complex subject is an iterative process that requires frequent reviews of progress and design decisions.

(c) Collecting, structuring and distributing the history of knowledge gained over the last 40 years is a formidable task. It requires a variety of methods and a great deal of patience and persistence.

4. CONCLUDING REMARKS

Tasks the Analyst Can Attack Using This Tool
The beginning analyst will use this tool to learn the step-by-step procedure for running the ODP. In this learning process, the analyst will be aided by the working examples of process flow and input and output, the tutorials (e.g., the set of Navshell tutorials), and the information provided about the program at varying depths of viewing.

The experienced analyst will use this tool to answer specific questions concerning individual parameters, parameter types and defaults, array sizes and syntax. One can then follow readily accessible links to find related parameters and investigate their interactions.

Both the beginner and the expert analysts will seek the answer to a myriad of specific questions such as:

How does one model the physical spacecraft structure?
How does one build a solar pressure model?
How does one deal with small forces?
How does one iterate on stochastic parameters?
How does one process differenced Doppler data?
What is a B-Plane?

All users will also benefit from the tips and tricks reference. This feature provides general ground rules, and common pitfalls, mistakes and errors. Also available are links to a database containing translations of error messages and error numbers. This information, accessible via index and search capabilities, will help to de-mystify the OD process.

Results
The CBI tool has been described as a "mature product." It has been released for use by JPL personnel for pre-flight analyses and operational activities. Metrics will measure its effectiveness in meeting the requirements listed in Section 1. Maintenance in response to user comments and suggestions is continuing.

Future Enhancements
The current version of the CBI tool considers range and Doppler data. Possible future enhancements would be to add the processing of other data types such as delta-DOR (differenced differential one-way range), launch angles, and optical navigation measurements. Additional functionality may include a method for monitoring and approving user tips, web-based access to update content as required, parsing of additional case studies within the tool, and expansion of the tool to include new software developments.

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