TMO TECHNOLOGY DEVELOPMENT PLAN

Navigation:

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OBJECTIVE:

The Navigation work area long-term objectives are to (1) increase the efficiency, reliability, and accuracy of the DSN-based navigation process, (2) reduce the overall cost and effort of navigation operations, and (3) shape the evolution of the DSN's navigation capabilities to meet the needs of future customers.

GOALS and SIGNIFICANCE:

In order to meet our long-term objectives, intermediate goals have been set. Achieving these goals will provide specific, significant benefits to the DSN navigation process.

Goals	Significance
Develop new techniques to improve navigation performance without increasing costs	• Monitor and characterize anomalous spacecraft behavior in near real-time • Ensure efficient use of DSN tracking for - Discovery/SMEX class missions - Small Body missions - Unstable orbit missions
Develop new low cost-methods to streamline DSN navigation operations	• Decrease operations costs for modeling spacecraft • Minimize redundancy in software efforts for mission planning and navigation
Develop new automated navigation software systems to support future ground-based and on-board navigation efforts	• Consolidate efforts to create and maintain separate software systems for off-line, autonomous ground-based, and on-board navigation • Enable analysts to provide quick, near real-time navigation support in critical scenarios

PRODUCTS:

These products have been funded to help meet our goals in FY98. Some products are new tasks, while others have evolved from earlier efforts in this work area. Collaborative efforts have been identified.

		Development Phase at Start of FY98				
Product	**Customer**	**Concept**	**Design**	**Demo**	**Transfer**	**Approach/Comments**
Adaptive Interplanetary Navigation	All Missions, DSN		•			Performed jointly with the Univ. of Texas/Center for Space Research
On-Board and Ground-Based Navigation Tradeoffs for Close-Proximity Operations and Landing on Small Bodies	Future Missions, DSN	•	•			Identify interplay between ground and autonomous navigation for operations; work performed with Iowa State University
Navigation in Unstable Orbits and on Unstable Manifolds	Future Missions, DSN	•				Work performed with Iowa State University
Automated Maneuver Optimization	Future Missions, DSN	•				Intended to increase functionality of an automated spacecraft

						navigation system
Navigation Tracking Strategies and DSN Operations Requirements for Discovery and SMEX Class Missions	Future Missions, especially Discovery & SMEX Class	•				Evaluate data types and strategies to minimize costs of tracking and TMOD operations
Stepping Stone Approach to the Next Generation Navigation Software System	All Missions	•	•			Builds on 'lessons learned' from successful ARTSN prototype

DESCRIPTION:

There are trends underway which must be understood in order to meet the long-term objectives of the Navigation work area:

- *Science and technology objectives of deep space exploration will continue to be met with a growing number of small, inexpensive missions*. As things stand, these missions will heighten the competition for DSN tracking resources. Also, the funding patterns for these missions do not generally allow for a team of navigation analysts to be dedicated exclusively to any particular mission,
- *The current cost-constrained environment will continue for the foreseeable future*. In order to offer additional new missions the same navigation services, opportunities to consolidate development of software tools and standardize operations should be exploited.
- *The role of autonomy in deep space exploration continues to grow*. Some of these new missions are relying on autonomy, both on the ground and on-board the spacecraft, to minimize processing turnaround time between data receipt and the creation of new spacecraft commands.

The tasks in the Navigation work area address these trends, and offer realistic solutions and benefits to the DSN-based navigation process. For example, the adaptive filtering collaboration with the University of Texas / Center for Space Research is an opportunity to lead the effort in standardizing the real-time modeling and monitoring of spacecraft. With an automated, adaptive filter running, navigators can cut time previously dedicated to manually updating a spacecraft model. Real-time anomaly detection will also be possible, and an analyst will be able to monitor multiple spacecraft simultaneously.

New missions will encounter deep space conditions rarely dealt with in the past, such as close proximity to small bodies and unstable orbits. Through collaborative efforts with Iowa State University (ISU), software tools will be built that many projects can use for mission, tracking, and navigation planning, thus eliminating the need for individual teams to re-create the same tools. By sharing these tools, new missions can design their activities around more sound (and efficient) tracking schedules and strategies earlier in their development.

Last year, this work area successfully demonstrated a prototype of an automated real-time spacecraft navigation system (ARTSN); in order to create an automated tool for these new missions to use, 'lessons learned' from this experience must be applied to a new version of this software. The new architecture will result in long-term automated software maintenance and extension savings. One major proposed extension to this automated system is the addition of an automated maneuver optimization scheme; this capability will give future mission designers a powerful new navigation option where quick maneuver design is critical to mission success.

DELIVERABLES:

- Demonstrate automated adaptive monitoring of spacecraft in interplanetary cruise using an adaptive filter bank, and assess the performance of the system (with University of Texas Center for Space Research)
- Develop tradeoffs between on-board and ground-based navigation activities for close-proximity operations and landing on small bodies, using the NEAR and Champollion scenarios as examples (with Iowa State University)

- Analyze and identify the basic navigation and tracking concerns encountered when orbiting in an unstable orbital environment, such as found in Libration point missions or missions utilizing multiple flybys in a planetary satellite system (with Iowa State University)
- Develop algorithms and tools for an automated trajectory correction maneuver (TCM) optimization system to complement and increase the functionality of an automated spacecraft navigation system.
- Evaluate navigation data types and strategies for future missions consistent with minimizing tracking costs and navigation operation support, and assessing the impact of these strategies on TMOD operations.
- Use 'lessons learned' from quick-prototype ARTSN approach to create a navigation software suite which encompasses more of the domain knowledge of the existing (non-real-time) navigation software suite

RESOURCE REQUIREMENTS BY WORK UNIT:

	JPL Account #	FY98	FY99	FY00	FY01	FY02	FY03
AUTO NAV AND ANAL SYS	***412-41603-312***	70					
OPT TRACKING CONCEPTS	***412-41604-312***	40					
NAV UNSTABLE ORBITS & MANIFOLDS	***412-41605-312***	30					
AUTO MANEUVER OPT	***412-41606-312***	110					
NAV TRKNG & DSN OPS REQ DISCRY	***412-41607-312***	40					
NXT GEN NAV SW SYS	***412-41608-312***	250					
Navigation Advanced Development	***412-41690-312***	0	471	451	442	459	459
Total		540	471	451	442	459	459
Total Workforce		2.68	2.94	2.82	2.76	2.87	2.87

TMO TECHNOLOGY TASK DESCRIPTION

TITLE:	Adaptive Interplanetary Navigation
WORK UNIT IN WHICH FUNDED:	AUTO NAV AND ANAL SYS (412-41603-312)
WORK AREA:	Navigation

BRIEF TECHNICAL SUMMARY:

Task Statement: *Develop and demonstrate an adaptive sequential orbit determination software suite prototype for processing radiometric ground-based measurements for highly-accurate navigation and event detection during interplanetary cruise and planetary approach to support JPL missions*.

The main task for this year is to demonstrate the utility of the adaptive filtering approach for orbit determination in a realistic mission setting. A filter bank will be constructed using the TMO-sponsored Automated Real-Time Spacecraft Navigation (ARTSN) system prototype as the basic building block of a bank using a gating network for regulation. Archived Mars Pathfinder cruise range and Doppler data will be processed with the adaptive filter bank. The ability of the adaptive filter bank to detect environmental and/or external changes during interplanetary cruise will be the main focus of the numerical experiments. One goal of the study will be to quantify the capability of the filter bank to detect significant spacecraft events (thruster firings, 'safe hold' attitude events, etc.) and reject misleading spurious data taken during interplanetary cruise.

JUSTIFICATION AND BENEFITS:

At present, there is a lack of systematic (and automated) approaches for selecting orbit determination filter parameters. Adaptive filtering algorithms fill this gap, and make it possible to detect environment and spacecraft changes in 'real-time' spacecraft monitoring. The resulting improvement in modeling will make it easier to navigate through interplanetary cruise and planetary approach with less tracking data, and extend the ability of an analyst to safely monitor more spacecraft.

It is envisioned that manned mission precision landing will require robust navigation algorithms that are simultaneously high-fidelity and implementable on-board. This technique can be extended for real-time use on-board a manned spacecraft on a precision landing approach trajectory.

APPROACH AND PLAN:

As a result of the Automated Real-Time Spacecraft Navigation (ARTSN) system testing, there is a set of recorded, unedited stream of Mars Pathfinder radio metric tracking data. As the Mars Pathfinder navigation team wraps up its reconstruction of the cruise trajectory, the cruise events (attitude changes, thruster firings, maneuvers, etc.) will be treated as the 'truth' model. The current (beta-version) of ARTSN will be the building block of the filter bank used to process this data; the ARTSN software suite will be licensed to the University of Texas at Austin for this sole purpose. One set of numerical experiments will be performed to see if the adaptive filter bank can correctly detect different events, and to characterize its ability to discern real events from misleading 'blunder points' which remain in these unedited tracking passes. Once the ability of the bank to detect these events has been established, the second objective is to assess the accuracy of the parameters being adjusted.
The preparatory work for this demonstration was performed in FY 97; the proposer has completed the description of the adaptive filter bank (including the regulating gating network), and is familiar with the ARTSN architecture, thus simplifying its integration into the filter bank.

DELIVERABLES:

(1) A validated gating network algorithm for regulation of an ARTSN filter bank.

(2) Demonstration of the adaptive filter bank, using unedited recordings of cruise tracking data, to the JPL navigation community.

(3) Final report, describing the detection and characterization results and recommendations, completed within one month of the conclusion of the task.

(4) A journal paper submitted to an appropriate journal reporting new developments to the navigation community. An associated conference paper will be presented.

RESOURCE REQUIREMENTS:

The projected savings come from the adoption of automated adaptive navigation systems by flight projects. With one new project picking up this service each year, an additional 0.75 WY/Y (~$80K) is saved in model assessing and orbit determination.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)	69	70				139
Workforce (WY)	0.1	0				0.1
Co-funding ($K)						0
Projected Savings ($K)			80	160	240	480

TMO TECHNOLOGY TASK DESCRIPTION

TITLE:	On-Board and Ground-Based Navigation Tradeoffs for Close-Proximity Operations and Landing on Small Bodies
WORK UNIT IN WHICH FUNDED:	OPT TRACKING CONCEPTS (412-41604-312)
WORK AREA:	Navigation

BRIEF TECHNICAL SUMMARY:

A study begun last year in the Navigation work area focused on defining the abilities and performance of ground-based and autonomous navigation and compared these two approaches. The study included a high-level assessment of mixtures of these approaches for two scenarios, a NEAR landing on Eros and the Champollion landing on a comet surface. That study will serve as a starting point for a more detailed analysis and characterization of the problem.

The study proposed here will analyze and characterize attainable orbit and surface delivery accuracies at small solar-system bodies for joint ground-based and autonomous navigation. The study will focus on the degree of cooperation needed between these navigation types, including analysis of ground-based only and autonomous-only. Traditional ground-based data types will be included (radiometric and optical) and a variety of autonomous data types will be analyzed (optical, beacon ranging and Doppler, altimetry).

This study will map out the true interconnections between ground-based and autonomous navigation approaches and formalize the optimal combination of them in terms of ground operation costs and tracking, delivery accuracy and performance. The results will be expressed in terms of reports and the delivery of general purpose S/W tools to analyze small-body orbiter and landing missions.

JUSTIFICATION AND BENEFITS:

Small solar-system body landing missions are currently in the planning stages (Champollion and Muses-C). Currently, there is a lack of understanding of the true interaction between ground-based and autonomous navigation, leading to unrealistic analysis of these missions, which in turn impacts scheduled DSN tracking time, predicted mission profiles and hardware design. This analysis will address this problem and provide a clear statement of the necessary level of co-operation between these approaches, which will allow for realistic trade studies in the development of small body orbiters and landers.

Specific endorsements of this research from the NEAR Navigation group and the Champollion project follow below:

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"The research proposed by Dan Scheeres to study the dynamics of landing a spacecraft on an asteroid or comet has relevance to the Near Earth Asteroid Rendezvous project. It is a stated goal of the NEAR mission to terminate the mission and end the orbit phase about asteroid 433 Eros by attempting a landing on the asteroid. The NEAR navigation team at JPL is involved in planning the orbit phase and landing, but since this is a first ever attempt to orbit a spacecraft about a small body, many of the tools and techniques for studying these phases do not exist. Some are being developed as needed during cruise, but much new work is required, especially to develop a viable landing scenario.

As task leader for NEAR navigation, I support Dan's proposed research and feel that our remaining work would benefit from the tools and techniques he derives for landing on a small body."

Bobby G. Williams, NEAR Navigation Task Manager

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"The Champollion project gives its endorsement to the research proposal entitled:

Ground-based and autonomous navigation trades for close-proximity and landing on small solar-system bodies (sic)

submitted to the TMO Technology Navigation Task by Dr. Daniel J. Scheeres. The results from this task are of interest to the Champollion project and may directly benefit it in the future."

Sincerely,

Dara Sabahi, Champollion Flight System Chief Engineer

APPROACH AND PLAN:

The approach to be taken consists of several tasks, some of which can be performed independently of each other and others which must be performed sequentially. All the tasks will leverage off of existing tools specifically built to model orbital dynamics about and close to small bodies. The tasks are highlighted below:

1. Build up a "quick-look" tool to characterize the accuracy and speed with which ground-based navigation data can estimate the shape, spin state and gravity field of an arbitrary body. Such analyses usually require that highly accurate, detailed orbit determination programs to be run, due to the lack of quick turnaround analysis tools. Such a tool will be constructed based in part on analytical results and reasonable simplifications.

2. Modify the above tool to generate estimates of the orbit determination uncertainties for analysis of the ground-based navigation performance.

3. Develop models of all autonomous data types that are deemed relevant to the current problem, determine their inherent accuracy and identify all relevant systematic errors that will impact their use as navigation devices. These include, but are not limited to, altimeters, radio beacons landed on the surface, one-way radiometric data and optical imagery of the body. Some of this work has already been accomplished during last year's task.

4. Incorporate these autonomous data types into the tool to enable navigation studies of close-proximity and landing orbits at small bodies. This will include the necessary calibrations which must be performed for the data types (i.e. radio beacon locations on the surface, accuracy of optical landmarks, etc.). Some of this work has already been accomplished during last year's task.

5. Use the developed tool to perform systematic studies of navigation delivery accuracies as a function of data type, small body characteristics, and mission profile. Results from the studies will be analyzed and the essential design rules and fundamental results will be distilled into a series of reports and simplified models.

The work will be performed by Dr. Scheeres and appropriate graduate students at Iowa State University in Ames, Iowa. At some point in the development of the tool it will be necessary to compare and, if necessary, calibrate it against the existing set of navigation operations and analysis tools at JPL. That work should be performed at JPL during the summers by the proposer or appropriate graduate student.

This work is a continuation of work performed in FY 97 by the proposer. That work involved a high-level analysis of the problem and identified the major areas in which work must be done. It also led to the development of the core set of software tools that will be modified to further this analysis, as described above. Results from that study will be published in a TDA progress report.

DELIVERABLES:

Deliverables from this task will be in the form of (1) reports describing the results of the analysis and detailing how they should be applied to evaluate real missions, and (2) simplified models of the navigation interaction and performance which can be used for design studies. An additional deliverable may be the actual tool used to perform the analysis, if its final form is amenable to general usage. The difference in allocated funding ($40K) versus proposed ($74K) for FY98 has resulted in a 4-6 month slip in deliverables from those listed in the original proposal.

<u>Schedule:</u>

10/98	Demonstrate the capabilities outlined in Items 1 and 2. Summarize to-date progress in Item 3.
1/99	Demonstrate the capabilities outlined in Items 1 through 3. Summarize to-date progress in Item 4.

10/99	Demonstrate the capabilities outlined in Items 1 through 4.
	Commence the analysis outlined in Item E (note, this analysis will have been on-going once Items A and B are completed).
	Commence comparison/calibration of tool against actual operations software, specifically cooperate with the on-going NEAR mission and perform relevant analyses of their end-of-mission landing on the surface of Eros.
1/00	Prepare report giving details of the results of the analysis.
10/00	Deliver suite of general purpose tools and models for use in designing and analyzing small-body close-proximity and landing missions.
1/01	Deliver the analysis tool for use by mission and navigation designers. (If future funding becomes available).

RESOURCE REQUIREMENTS:

With the adoption of these software tools by mission and navigation designers, redundant efforts are eliminated, saving on the order of $100K/mission at the rate of 1 mission/yr, starting as early as FY 99. This research will also help guarantee an efficient use of DSN tracking time for small body missions; these savings are believed to be at the few $10sK/yr level.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)	40	40	75	75		230
Workforce (WY)	0.2	0	0	0		0.2
Co-funding ($K)						0
Projected Savings ($K)			130	130	130	390

TMO TECHNOLOGY TASK DESCRIPTION

TITLE:	Navigation in Unstable Orbits and on Unstable Manifolds
WORK UNIT IN WHICH FUNDED:	NAV UNSTABLE ORBITS & MANIFOLDS (412-41605-312)
WORK AREA:	Navigation

BRIEF TECHNICAL SUMMARY:

Analyze and identify the basic navigation concerns encountered when orbiting in an unstable orbital environment, such as found in libration point missions or missions utilizing multiple flybys in a planetary satellite system. The navigation concerns to be analyzed and addressed are: propagation of orbit errors, optimization of tracking schedules for orbit determination, design and implementation of correction maneuvers, and overall design of the navigation system. The study will investigate using the properties of unstable orbits to optimize the tracking and performance of navigation operations.

The study will approach the subject using the mathematical tools of non-linear dynamics; the use of non-linear dynamic methods is warranted for several reasons: these tools are currently being developed for use in mission design and having a complementary set for navigation analysis would eliminate difficulties in translating results from one paradigm to another, navigation concerns have not traditionally been developed using these methods and could have large potential payoffs, the analysis of new missions utilizing such dynamics (e.g. GENESIS, Europa Orbiter) would be facilitated.

The study will leverage off existing work being performed by Dr. Lo which analyzes mission design issues in unstable orbital environments.

JUSTIFICATION AND BENEFITS:

Orbital missions utilizing advanced concepts in the design of trajectories are becoming more commonplace (GENESIS, Europa Orbiter, L1 and L2 missions). Traditional mission design techniques fail for these missions and recourse must be taken to the tools of non-linear dynamics. Traditional navigation analysis of these missions often becomes cumbersome and difficult due to the strongly unstable nature of these orbits and, if simply applied, may result in overly conservative designs which make such missions appear artificially expensive. A reanalysis of the basic navigation functions in these unstable dynamical environments will shed new understanding on how these missions should be flown and may yield spin-offs that can be applied to traditional navigation analysis approaches as well. The ability to better understand the navigation basics of flight in unstable environments may enable new classes of missions to be flown (such as Earth-Moon libration orbits) where traditional navigation analyses may require burdensome levels of tracking and monitoring.

The bottom-line benefits of this analysis will be a better understanding of navigation in unstable orbital environments, which in turn will be useful in optimizing spacecraft tracking schedules and minimizing the effort required in navigation operations of these mission types.

The GENESIS mission supports the approach addressed in this proposal.

APPROACH AND PLAN:

The approach to be taken is highlighted below:

1. Obtain sample trajectories that are of interest to current and future missions. Develop the necessary propagation tools to model the sample trajectories and generate similar classes of trajectories. The initial trajectories will focus on the Earth-Moon-Sun system and may also focus on the Jovian system and asteroid missions.

2. Analyze and experiment with the dynamics of orbit uncertainties in these unstable environments. The focus will be to determine the appropriate context in which to measure uncertainties and isolate the fundamental dynamical processes which lead to the orbit uncertainty dynamics. Initially, the study will concentrate on the uncertainty mapping due to gravitational effects alone, but will be extended to non-gravitational forces such as solar radiation pressure and stochastically varying accelerations acting on the S/C. Special focus will be given to the effects of resonances on the orbit uncertainty propagation.

3. Starting from task 2, investigate how the spacecraft uncertainty in phase space is reduced under trajectory measurements such as radiometric range and Doppler and other measurement types (e.g. optical imagery, altimetry, ...). Use acquired knowledge on how the uncertainties map to characterize the effectiveness of measurements taken at different points along the orbits. This phase of the study will ideally enable an optimized tracking schedule to be designed, taking advantage of good observational periods.

4. Starting from task 2 again, investigate the design and implementation of orbit correction maneuvers. The approach will account for the natural dynamics of the system in the design of trajectory correction maneuvers (TCMs) to minimize the correction magnitude and frequency of corrections. Development of autonomous maneuver design algorithms will also be investigated.

5. Synthesize the results of the study into a report and into a description of simplified tools and models that can be used in forecasting the level and periods of tracking needed for missions in unstable orbital environments, and in designing the navigation systems for missions that fly in unstable orbits.

As the work progresses, the tools will be tested and verified against new mission proposals that involve spacecraft flight in unstable orbital environments.

The Nonlinear Navigation Tool Modules developed at ISU shall comply with JPL LTool S/W Interface standards so that they appear as plug and play modules to the LTool user.

The majority of the work will be performed by Dr. Scheeres and appropriate graduate students at Iowa State University in Ames, Iowa. Supporting work will be performed by Dr. Lo at JPL. During the period of the contract it will be necessary to compare and calibrate results against the existing set of navigation operations and analysis tools at JPL. That work will be performed by Dr. Scheeres or appropriate graduate student on-site at JPL.

JPL shall provide the baseline trajectories and the associated invariant manifold trajectories to ISU. JPL shall provide the visualization tools for the above trajectories and manifolds.
Nondisclosure Agreement: Material provided by JPL to ISU shall be used only by Scheeres' research group and shall not be used for non-JPL work except as agreed to by JPL on a per case basis and documented in writing.

DELIVERABLES:

Deliverables from this task will include reports describing progress and giving description of the analytical results. Additional deliverables will be simplified models to use in forecasting the amount of tracking necessary for navigation in unstable orbits and the necessary navigation staffing profiles needed to support such missions. The difference in allocated funding ($30K) versus proposed ($99K) for FY98 has resulted in a 4-6 month slip in deliverables from those listed in the original proposal.

2/99	Demonstrate the capabilities outlined in Item 1. Summarize to-date progress in Item 2.
11/99	Demonstrate the capabilities outlined in Items 2, 3 and 4.
2/00	Prepare report giving details of the result of the analysis.
11/00	Deliver suite of general purpose models and tools for use in designing and forecasting necessary navigation and tracking support for missions in unstable orbital environments.

Earlier deliveries of the general purpose models and tools will be given throughout the term of the contract.

RESOURCE REQUIREMENTS:

With the adoption of these software tools by mission and navigation designers, redundant efforts are eliminated, saving on the order of $100K/mission at the rate of 1 mission/yr, starting as early as FY 99. This research will also help guarantee an efficient use of DSN tracking time for unstable-orbit missions; these savings are believed to be at the few $10sK/yr level.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)		30	100	101		231
Workforce (WY)						0
Co-funding ($K)						0
Projected Savings ($K)			130	130	130	390

TMO TECHNOLOGY TASK DESCRIPTION

TITLE:	Automated Maneuver Optimization
WORK UNIT IN WHICH FUNDED:	AUTO MANEUVER OPT (412-41606-312)
WORK AREA:	Navigation

BRIEF TECHNICAL SUMMARY:

Develop algorithms and tools for an automated trajectory correction maneuver (TCM) optimization system to complement and increase the functionality of an automated spacecraft navigation system.

There are presently numerous approaches to solving optimization problems, and each has its own merit under specific circumstances. Frequently, existing algorithms suffer convergence problems in the search for the absolute optimal solution or are ill-suited for the specific maneuver optimization application at hand. The current algorithms were not intended for an automated approach.

A robust system is necessary to solve the maneuver optimization problem in an automated fashion. This includes improved algorithms and a paradigm shift in the use of these algorithms toward an automated system. The study will analyze and assess different optimization methods (stochastic, linear, non-linear) applied to common spacecraft maneuver optimization scenarios. The challenge is to modify existing and/or develop new algorithms to create a robust automated maneuver optimization system.

JUSTIFICATION AND BENEFITS:

Current progress is being made in the orbit determination area of automated real-time spacecraft navigation (ARTSN). An automated maneuver design/optimization function is necessary to utilize this capability and strive toward future navigation autonomy. Optimization methods are currently used routinely in ground operations to significantly reduce spacecraft propellant requirements. A complete autonomous navigation system requires the maneuver optimization capability.

This proposal represents a necessary step in the progress toward an autonomous on-board maneuver optimization capability. Future autonomous maneuver optimization combined with on-board orbit determination will significantly reduce the navigation operation effort and cost. The scope of this savings is multi-mission.

Specific endorsement has been obtained from the Ice and Fire Preproject, especially for possible use in the Europa Orbiter mission.

APPROACH AND PLAN:

The approach is highlighted as follows:

A) Investigate existing optimization algorithms and approach methods (statistical, linear, non-linear). Identify promising approaches for further study and analysis.

B) Set up a software testbed to apply numerous optimization techniques to specific spacecraft maneuver optimization problems. Sample problems include: n-maneuver optimization (n=1,2,3,...) to a fixed target (1,2, or 3 target variables), n-maneuver optimization to a target with constraints, and multiple flyby trajectory optimization with constraints. Analyze and experiment with algorithm capabilities and problem areas.

C) Select promising algorithms for specific spacecraft optimization problem. Assess capabilities with more difficult convergence problems. Experiment with algorithm modifications and usage techniques to improve robustness. Include various weighted solutions to minimize propellant expenditure assuming different spacecraft Δv implementation configurations.

The study will coordinate and complement efforts to solve the more difficult convergence problems with the CIP "CATO Enhancements" proposed by Greg Garner, Section 312.

D) Based upon the results and algorithms developed in item C, design an automated maneuver optimization system for the various mission profiles outlined in item B. Test the robustness of the system using monte carlo methods to statistically vary the initial state and examine the automated maneuver optimization results. The sample size will be determined by resource limitations.

E) Combine results into a report and describe tools and capabilities that can be used in an automated maneuver optimization system. Demonstrate the automated maneuver optimization capability with the ARTSN system.

Responsibility and oversight of the task will be performed by Christopher L. Potts, Section 312. Mathematical support provided by Fred T. Krogh, Section 395 and Professor John Michel of Marietta College in Marietta, Ohio. Larry Bright, Section 312 to provide consulting and assist with applied optimization techniques.

DELIVERABLES:

A final report will include a description of the analysis and the results. Additional deliverables will be algorithms and documentation including details of capabilities for use in automated maneuver optimization systems.

8/98 Summarize results from item A.
Demonstrate capabilities in item B.
8/99 Demonstrate capabilities in items C and D.
5/00 Prepare detailed report of analysis results.
8/00 Deliver algorithms with documentation to use in automated maneuver optimization systems.
Demonstrate capabilities with the ARTSN system.

RESOURCE REQUIREMENTS:

The Ice and Fire Preproject has volunteered co-funding.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)		110	200	120		430
Workforce (WY)		0.74	1.4	0.8		2.94
Co-funding ($K)		10	30	10		50
Projected Savings ($K)						*

* Potential for substantial multi-mission cost savings beyond FY00 by reducing maneuver analysis support during operations by a minimum of 50%. Over the 8 year Galileo prime mission, this would have resulted in a savings of approximately $2.2M (16 work years).

TMO TECHNOLOGY TASK DESCRIPTION

TITLE: Navigation Tracking Strategies and DSN Operations Requirements for Discovery and SMEX Class Missions

WORK UNIT IN WHICH FUNDED: NAV TRKNG & DSN OPS REQ DISCRY (412-41607-312)

WORK AREA: Navigation

BRIEF TECHNICAL SUMMARY:

Future Discovery and SMEX deep space missions such as Stardust, DS1, and Magsonas are proposing navigation tracking strategies which rely on brief infrequent passes of tracking data for orbit determination. The driver for these strategies is to minimize the cost to the project of DSN antenna time and navigation operation support. The objective of this proposal are as follows:

a) to evaluate navigation data types and strategies consistent with minimizing tracking costs

b) to assess the impact of these strategies on TMOD operations

JUSTIFICATION AND BENEFITS:

It is expected that the results of this study will identify data types and tracking strategies which are best suited for minimizing antenna tracking costs. It will also identify the effect of these procedures on TMOD operations and calibrations requirements. For example, missions will be requiring fewer and shorter tracking passes which assumes a higher degree of reliability for the DSN. It also places increased significance of the accuracy and reliability of the DSN calibrations for the navigation data types-specifically range and possibly timing calibrations.

APPROACH AND PLAN:

Deep space navigation has typically relied on daily horizon-to-horizon passes of two-way Doppler for directly determining the angular position. This data augmented with range and collected over several days, directly determines the spacecraft position and velocity. The mode of operations proposed by Discovery class missions is to infer the spacecraft flight path by the change in geometry over several weeks as determined from the brief (2-4 hour) weekly passes of range and Doppler. This proposal will investigate strategies and data types consistent for this environment. It will investigate the feasibility of using dual station data types such as VLBI. In particular it will attempt to assess if reliability, cost, and operation ease are suitable.

DELIVERABLES:

Recommendations for tracking strategies that should be pursued for Discovery/SMEX class deep space missions. Evaluation of the impact of these procedures on TMOD scheduling and calibration procedures.

RESOURCE REQUIREMENTS:

This research will help guarantee an efficient use of DSN tracking time for Discovery/SMEX class missions; these savings are believed to be at the $30K/yr level.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)		40				40
Workforce (WY)		0.26				0.26
Co-funding ($K)						0
Projected Savings ($K)			30	30	30	90

TMO TECHNOLOGY TASK DESCRIPTION

TITLE:	Stepping Stone Approach to the Next Generation Navigation Software System
WORK UNIT IN WHICH FUNDED:	NXT GEN NAV SW SYS (412-41608-312)
WORK AREA:	Navigation

BRIEF TECHNICAL SUMMARY:

In FY 97 the TMO Technology Navigation work area successfully demonstrated a capability to perform real-time orbit determination of the Mars Pathfinder spacecraft during interplanetary cruise using radio metric tracking data, as well as current-state and epoch state measurement processing. In order to accomplish this objective, it was necessary to re-package the relevant domain knowledge (from the DPTRAJ/ODP software suite) into a software system named ARTSN (Automated Real-Time Spacecraft Navigation). The hallmarks of the ARTSN software architecture that made the real-time demonstration possible included the following:

- The system is data-driven; updated solutions are triggered by the arrival of the data, not by human intervention.
- Historical program links have been discarded. The traditional program functions are contained in an integrated system with each module capable of talking to the others. With the elimination of intermediate links, no redundant re-entry of inputs is necessary.
- The object oriented programming techniques used in the system design have already proven their value by reducing the cost and time needed to add new features. The flexibility of the system has enabled testing of multi-spacecraft simulations, spacecraft-to-spacecraft data types, lander scenarios, and many other non-standard scenarios.

The ARTSN prototype enabled the rapid iteration of several navigation software designs. Based on the success of this project, it is proposed that the lessons learned creating a real-time navigation software system be applied to a much larger portion of the knowledge domain of the current navigation software set. The objective is to use modern programming techniques to create a software system with these characteristics:

- Modularity, so sub-systems can be created from the building blocks to perform specialized functions such as real-time or on-board navigation.
- Flexibility, so new capabilities can be easily added, enabling the support of a wide variety of current and future mission scenarios.
- It will be comprehensive, so that the breadth of the current capability can be eventually encompassed by the design. Existing code will be re-implemented or wrapperized to conform to the new interface, on a case by case basis.
- It will incorporate a flexible user design that will be well documented and easier to use than the current system.

JUSTIFICATION AND BENEFITS:

Historically, the DPTRAJ/ODP software ensemble has been continually evolving, with successive versions reporting new capabilities. This proposal represents a departure from that approach. Why is such a change needed? There are three parts to that answer:

<u>Cost of Software Extension and Maintenance:</u> The design of the current system was never meant to encompass all of the capabilities that have been or plan to be added. As such, it is very difficult to add new modules and the programmer must have an in depth working knowledge of the complete system in order to safely make changes to the code. Fewer and fewer of the creators of DPTRAJ/ODP links and utilities are around to maintain this code, and it is expensive and time consuming to train someone for this task.

Object oriented design and modern programming techniques can help alleviate this burden in two ways. First, by creating a system with well-defined interfaces and modules, a technically proficient newcomer can be used to safely create new modules without perturbing the existing capabilities. This translates into much lower costs for software upgrades. Second, these modules allow a building-block approach to

applications. Real-time and on-board systems can be built from the same blocks as the traditional (validated) off-line ground navigation system.

Of course, the initial costs of this proposal are not trivial, but there will be a long-term payoff. Currently, separate systems are funded for ground, real-time, and on-board navigation efforts. The consolidation of these systems into a modern architecture will lower the long-term maintenance costs as well as cost to the end-user.

The Changing Role of Navigation Software There are many efforts, both on-lab and in industry, to establish different levels of navigation autonomy, both on the ground and on-board a spacecraft. What does the future breakdown of real-time vs. after-the-fact processing look like for JPL missions? It is difficult to predict the timetable, but the trend is clear; there is an growing need (from the X2000 program, for example) for software to perform real-time navigation tasks (orbit determination, maneuver design, etc.). These capabilities cannot be achieved with an evolutionary change to the existing software set; the domain knowledge must be recast into a new architecture which can support both scenarios.

User Interface and Training The current system is difficult and time consuming to learn; with few exceptions, training requires an extensive 'mentor/apprentice' working relationship. Previous efforts (NOWW, XNAV) to encapsulate the existing software with a user-friendly interface were hampered because the current software was never intended to be used in that manner. A modular approach to a user interface will allow traditional text-based inputs as well as graphical front ends. The interface can then be tailored to the needs of specific projects or users.

APPROACH AND PLAN:

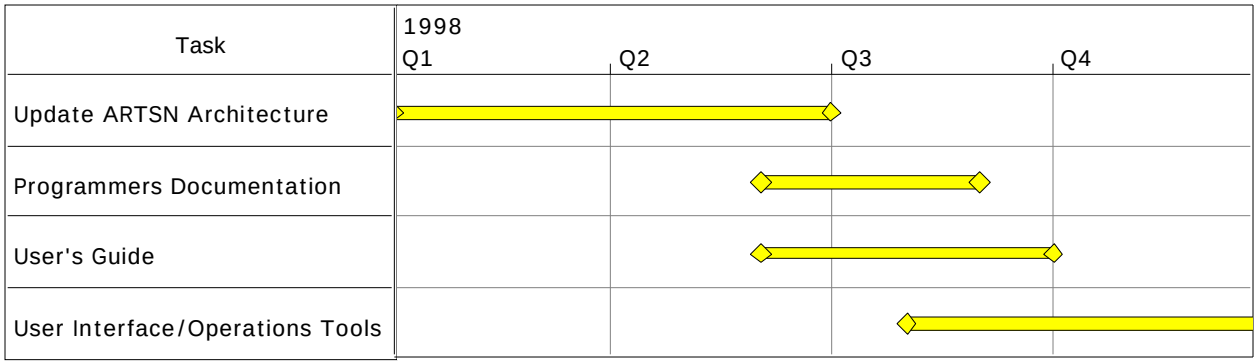
The current ARTSN system will require several improvements and updates to be able to cover the current capabilities of DPTRAJ/ODP. The major task will be the update of the system architecture and the writing of complete documentation for the system. The money and workforce do not exist this fiscal year to allow for a large increase in the number features in the current ARTSN system. The objective of the architecture update and documentation is to allow these features to be added at a later date by a larger number of people with a minimum of work. A second task of this effort in FY98 will be the design and implementation of several tools to improve the usefulness of the software to operational navigation teams. This includes an updated residual plotter and data visualization tool (for real-time applications and data editing) and a file management tool (for easy manipulation, description, and archival of processing runs).

DELIVERABLES:

In summary, the primary intended deliverable is an updated ARTSN architecture with the following improvements:

- Improved object-oriented design for later incorporation of the domain knowledge of DPTRAJ/ODP
- Full programmers documentation and user's guide
- User interface modules and utilities to allow system to be used operationally by navigation teams.

Due to the uncertainty in funding with this particular task, it is not prudent to forecast deliverables beyond the end of FY98.



RESOURCE REQUIREMENTS:

By consolidating future development of software suites for manual and autonomous ground-based and on-board navigation, the savings will conservatively be on the order of 3-5 WY/Y.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)		250	250			500
Workforce (WY)		1.64	1.59			3.23
Co-funding ($K)						0
Projected Savings ($K)			600	600	600	1800