

IPN-IS TECHNOLOGY DEVELOPMENT PLAN

Navigation and Radio Metric Tracking

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OBJECTIVE:

Develop new navigation and tracking systems and technology elements to enable and enhance challenging mission scenarios requiring autonomy, formation flying, or coupling of attitude and flight path determination (integrated guidance, navigation and control, e.g. dynamic entry, descent, and landing) by developing capabilities for contending with (1) new force environments (e.g. small body and satellite orbital operations); (2) low cost operations goals; (3) advances in measurement technology; and (4) unique science opportunities (e.g. comet or asteroid rendezvous and sample return).

GOALS and SIGNIFICANCE:

Goals: Develop and demonstrate key new technology elements (sensors, algorithms, models, design tools, and software) required for: guidance, navigation and control (GNC); small body navigation; precision formation flying; and proximity telecom/tracking systems. Develop an architecture and roadmap for navigation and metric tracking technology development, including technologies needed for integrated GNC. Coordinate technology development activities with Mission Data Systems (MDS), Next Generation Navigation Software, and flight projects. Employ novel use of GPS as a testbed for proximity autonomous interplanetary tracking systems. Develop new automated ground and space-based navigation techniques, models and fault detection to improve performance and reliability, minimize costs, and enable new science opportunities.

Significance: The technology development in this Work Area (NRM) supports key NASA/JPL initiatives for Mars, deep space, and outer planet exploration and sample return. NRM develops enabling capabilities for Mars, New Millennium, Discovery, small body, sample return, and interferometry missions; reduces tracking and GNC costs by an order of magnitude under certain circumstances; and supports NASA partnerships with industry. The strategy of using GPS and other flight opportunities as low-cost testbeds for new technologies will serve to lower autonomous GNC development costs overall. NRM technology also modernizes and streamlines operations while reducing mission risk.

PRODUCTS:

Key products for FY02 include: navigation mission design tools; prototype software for ground and space operating environments; prototype software for onboard autonomous navigation integrated with telecommunications; new optical navigation sensor prototypes; and new subsystems for metric tracking. This Work Area is comprised of a set of coordinated tasks that enable end-to-end technology development. Technology products are developed in a manner consistent with roadmaps and architectures for tracking and navigation development. Generally, the process begins with the development and test of algorithms and prototype software. New tracking sensors are also constructed in the course of some of the tasks. Hardware and software elements are generally tested in technology testbeds, starting on ground testbeds which simulate the mission environment and leading to flight demonstration opportunities. The next phase of NRM technology development may include proof-of-concept testing for new navigation approaches in new mission environments. System-level feasibility demonstrations may be conducted, once again utilizing real space platforms where available. Current customers and users will include Starlight, Terrestrial Planet Finder, ST-5, Mars Projects, Europa missions, LISA, comet and asteroid missions, DSN Navigation System Services, Next Generation Navigation Software Implementation, and MDS.

DESCRIPTION:

This Work Area is focused on the following evolving key needs of NASA/JPL deep space exploration missions:

Challenging new capabilities never before exercised. These include higher precision and accuracy for challenging targeted planetary exploration mission scenarios that require a greater degree of navigation control than was ever possible before. These scenarios include narrower corridors for approach navigation and entry, descent, and landing (EDL). To meet the same navigation accuracy metric at outer planetary body distances as has been required for inner planetary bodies, a greater degree of angular accuracy must be achieved. Rather than determine where a spacecraft has landed on a planetary body after the fact, new mission profiles require that the spacecraft be navigated in real-time or close to real-time to a specific location on the surface. In many cases, these capabilities are driven by more demanding science goals and requirements.

Autonomous navigation in the vicinity of and on the surface of planetary bodies. The ability to direct a spacecraft to a specific location, retrieve a sample, and then find and rendezvous with another orbiting vehicle requires a greater degree of autonomy and coordinated operations for future missions. The greater complexity of these missions also requires that cheaper and smaller spacecraft be utilized. Such spacecraft can be more complicated to model and navigate. With multiple vehicle operations and proximity coordinated activities, a tighter integration of navigation and telecom is needed, especially for spacecraft-spacecraft and spacecraft-ground communications and tracking. This in turn requires real-time navigation and decision/control, particularly where long intervals between commanding and communication can markedly decrease the science return for rovers and/or spacecraft with limited lifespans. Precision formation flying and coordinated navigation of multiple vehicles is also relevant for deep space missions, such as for interferometers on separated spacecraft.

Lowering risk. While simultaneously employing some of the above new capabilities, it is required that we develop new technologies that can lower overall mission risk. This can be achieved by improving the capability of additional, complimentary data types over traditional navigation observables.

Lowering costs. With infinite resources, most of the above new capabilities could probably be realized. However, unless cost savings can be implemented, many of JPL/NASA's ambitious plans to explore the solar system will have to be put on hold. Lowering costs through properly applied new technologies can be considered a key element of the overall vision by which new capabilities can be achieved in multiple areas simultaneously given the financial constraints that must be accommodated. By lowering operational costs, additional resources can be freed up to contribute to developing new capabilities and taking additional measures towards lowering risk. Without a significant advance in onboard autonomy, navigation will be too costly to permit ambitious and simultaneous missions to multiple planetary targets. The entire mission cycle must be considered, including mission design, cruise operations, maneuver planning, approach navigation, and EDL. The first step is to develop the new technologies, and the second step is to implement them robustly, safely, and in a manner that requires minimal labor and DSN antenna time.

The Work Area technology for FY02 is divided into three key thrusts: navigation and mission design; advanced tracking and GNC testbeds; and integrated sensors for navigation and telecom. Each funded task is identified below in the Resource Requirements section as belonging to one of these thrusts.

The **Navigation and Mission Design** thrust includes five tasks. The *Autonomous and Adaptive Interplanetary Navigation* task has a focus on use of innovative filtering methods to enable very tight (100m) landing requirements to be met. This year's effort is a continuation of FY01 activities on the EDL navigation autonomous monitoring component using the Hierarchical Mixture of Experts (HME) algorithm. The HME is a multilevel neural network of "experts," each with different internal models that operate in parallel with each other. In our problem, the "experts" are individual trajectory filters with different measurement and dynamic models. The neural network continuously monitors these "experts" in real time and "learns" which filter model best matches measurement data. The FY02 effort will continue enhancing the HME to handle more sophisticated mission scenarios (i.e. such as detection of discrete events like parachute deploy and a greater range of atmosphere modeling uncertainties) and expand the measurement types that can be processed to include on-board gyro data and external radiometric data (e.g., from a Mars Network asset). The *Spacecraft Dynamics and Navigation in Unstable Environments and in Close Proximity to Small Bodies* task combines two research thrusts from previous years into a single, integrated proposal

spanning several diverse issues in spacecraft navigation and control. The first research thrust is focused on close proximity navigation and operations of a spacecraft in the vicinity of a small solar system body (such as an asteroid, comet, or Kuiper belt object). The second research thrust investigates the effect of orbit instabilities and non-linearities on the orbit determination and navigation performance of a spacecraft. The *Aeroassist Software for Mission Design and Navigation* task will analyze the use of atmospheric forces to improve mission performance and significantly reduce mission cost. It includes applications such as aerobraking, direct entry, descent, and landing, aerocapture, aeromaneuver, atmospheric guidance, aerogravity assist, planetary airborne vehicle (e.g. Mars airplane), aerobots, hazard avoidance, precision landing, planetary ascent dynamics, and earth return dynamics. The objective is to develop a general-purpose state-of-the-art aeroassist program that handles these applications in a user-friendly environment. The proposed software will unify aeroassist modeling for mission design and navigation for the first time anywhere. *Low-Thrust Spiraling Trajectory Design Techniques* will develop trajectory design techniques and algorithms to enable the modeling, design and optimization of low-thrust spiraling trajectories near massive bodies as a sub-phase of an interplanetary trajectory. Existing techniques and tools have only a simple, analytic model for determining a crude estimate of the time and propellant required to capture to or escape from a circular orbit around a planet. Current tools do not allow any of the following essential elements of a complete trajectory design to be accomplished for trajectories that include such spiraling phases: (1) generation of a complete description of the spacecraft path during the spiraling phase; (2) incorporation of the spiraling phase into an end-to-end interplanetary trajectory; and (3) end-to-end trajectory optimization. An optical navigation sensor technology task, *Flight Design of an Autonomous Optical Navigation System*, will develop a preliminary but detailed flight design of an autonomous optical navigation system for future missions. The basic goal is to combine the optics, detector, electronics and a local pointing device (a two axis gimbal) into a low mass (less than 1.5 kg), low volume (20 cm x 20 cm x 20 cm total envelope including gimbal motion), low power (few watts) system which could be easily bolted onto a wide range of spacecraft types and which could handle key navigation functions for those projects. (As a comparison, star trackers have masses of 3 or more kg.) The majority of this effort will be directed toward the detailed analysis and the mechanical design of the low mass (less than 0.5 kg) two-axis gimbal, including a detailed layout with detailed design drawings using the known MUSES-CN motors and gears that have been baselined for the gimbal, and stress and bearing analysis. The drawings are a fundamental mechanical product needed for later fabrication of parts and to insure that motors, gears and wires all fit together.

Advanced Tracking and GNC Testbeds includes three tasks. The *ST-5 Testbed for Mars Network Proximity Navigation Technology* task will exploit a unique opportunity presented by the ST-5 constellation mission to flight-test prototype onboard software modules and algorithms for radio-based proximity navigation. This will significantly reduce the risk to the Mars Network stemming from flying to Mars a first of a kind software that hasn't been flight-tested. The software includes algorithms and code for: autonomous navigation based on spacecraft to spacecraft links; real time spaceborne positioning of ground assets ("reverse" orbit determination); and real time onboard orbit determination based on ground to space links. ST-5's radio metric measurements include 1-way and 2-way Doppler, as well as 1-way and 2-way phase and range. Autonomous navigation capabilities based on these measurements have never before been demonstrated in flight, or implemented in flight software, and hence are at low TRL of 3. Our goal is to raise the TRL for these key technologies to 7 by developing the necessary algorithms and prototype flight software, and demonstrate their performance in a relevant space environment, but one where truth is readily available (via GPS). The task for *Simulation Testbed for Evaluation of Optical Correlator and Other Navigation Sensors* will implement and GN&C simulator that demonstrates how the Miniature Optical Correlator (MOC) can be integrated into future missions and used operationally for EDL. In addition, we will develop metrics for measuring the performance of the MOC and measure the performance of the breadboard correlator in a closed-loop, integrated testbed with realistic GN&C. The testbed will then be expanded to include other sensors to serve as a tool for performing similar, high-fidelity trade studies for EDL and related mission phases. The analysis will include: representative or actual GN&C algorithms for small body (Eros, comet) and planetary landing (Mars, Titan), a combination of actual and simulated terrain from entry through preparation for landing (down to 1 meter), high-fidelity spacecraft dynamics (6DOF+), and sensor and actuator models for each scenario. The work area includes a task that focuses on high precision tracking using the DSN ground network, *One-nrad DDOR and Error Budget Determination*. DDOR (delta-differential one-way range) is a interferometric (VLBI) data type that is planned for use in the sequence of Mars missions over the next ten years as well as in other missions such as Stardust and Deep Impact. The DDOR data provide extremely high accuracy plane of sky tracking measurements. These data are considered critical for high precision targeting mission

scenarios as well as for providing additional data to supplement conventional Doppler/range data for navigation safety and resiliency. There are currently four main areas of concern regarding the DDOR measurement technique that urgently require research and development if DDOR accuracy is to be improved from the current 5-10 nrad level to the 1 nrad level. In FY02, this task will focus on the top two priorities, which are improvement of ionospheric calibrations, and improvement of the planetary frame tie.

The **Integrated Sensors for Navigation and Telecom** thrust in FY02 is comprised of the *Software Reconfigurable Transceiver* task. This work will extend the performance testing and functionality of the software reconfigurable radio (SRR) prototype previously developed in FY01 to mature the technology to the point where on-the-fly software reconfigurability for a representative set of plausible spacecraft mission operations scenarios can be demonstrated and performance quantitatively analyzed. The demo and technology will demonstrate feasibility of rapid-prototyping for rapid space-qualified implementations of communications, navigation, and science signal processing functions over and above the current state-of-the-practice for NASA missions; show viability of creating a long-life communications infrastructure (such as for use in and around Mars) enabled by on-board processor reconfiguration; and demonstrate and measure performance of greatly improved science instrument and processing capabilities through on-orbit, science driven reconfiguration. Towards this end, a second physical modulation waveform (in addition to the currently implemented BPSK) will be demonstrated as well as on-the-fly modulation switching and operation of multi-channel receive/transmit channels.

INTERDEPENDENCIES:

The **Optical Correlator EDL Prototype** expects to receive significant co-funding in the amount of approximately three times the IPN contribution from BMDO and NWSC. The co-funding will cover the cost hardware and software development and test of the Miniature Optical Correlator.

The **Aeroassist Trajectory Optimization** effort expects to receive funding from DNP at a similar level to IPN.

The **In-Orbit Testbed for Mars Navigation** depends on several flight experiments for flights of opportunity to demonstrate the new technologies in a representative space environment. These include SAC-C and ST-5. SAC-C carries a Blackjack GPS flight receiver in which some of the new algorithms and prototype software will be demonstrated. ST-5 will be used to demonstrate formation flying and proximity telecom/navigation with multiple vehicles in Earth orbit under characteristics that are relevant for future Mars missions. This effort also is utilizing real-time navigation technologies under development in the AIST NASA program that will be used for the first time in space. For the rover portion of the testbed, other programs will be needed for refurbishment of the LEO-T ground tracking system.

The **DDOR** technology task will depend on data collection that is planned under the auspices of the Mars exploration program and the DSN overload task in the IPN-IST directorate.

DELIVERABLES:

Delta-DOR measurements of Mars '01 Odyssey and MGS with respect to background radio sources (Q2), IPN Progress Report, including recommendations on improving tracking system accuracy (Q4).

Flight test of prototype on-board software modules and algorithms for radio-based proximity navigation (Q2).

Integration of the Miniature Optical Correlator (MOC) into the DSENDS EDL simulator (Q2), performance evaluation report on descent image tracking algorithms (Q4), demo showing quantified performance of MOC in an EDL simulation (Q4)

A preliminary structural analysis of a two-axis gimbal for an autonomous optical navigation system (Q2), followed by a preliminary design (Q3) and CAD drawings (Q4) for a flight system.

Evaluation report of candidate control strategies (Q2), low-thrust spiraling trajectory design tool including shadowing and other force models integrated with best performing control strategies (Q4), user guide (Q4)

An aerobraking module for MONTE, a Next Generation Navigation Software product, with updates generated for the functional requirements and design document (Q4).

An enhanced prototype real-time autonomous navigation algorithm of use during EDL and an infusion plan to for transitioning the prototype simulation and analysis system into MONTE (Q4).

Demonstrate implementation of second physical modulation waveform (first was BPSK) (Q3) in the software reconfigurable transceiver testbed. {choice will depend on efficiency and SNR characteristics}; demonstrate and document on the fly modulation switching and multichannel receive/transmit channels (versus current single, full duplex channel) (Q4)

Incorporate small body dynamic models into DSENDS (Q3); test/validate and deliver written report documenting accomplishments and results (Q4).

RESOURCE REQUIREMENTS BY WORK UNIT

	Proj #	Task Number	FY02	FY03	FY04	FY05	FY06
AEROASSIST S/W FOR MSN DESIGN & NAV	100713	70.200.34.5.1002	125				
FLT DESIGN AUTO OPT NAV SYSTEM	100713	70.200.34.5.2002	175				
CLOSE PROX NAV NEAR SM BODIES	100713	70.200.34.5.3001	100				
ADAPTIVE INTERPLANETARY NAV	100713	70.200.34.5.3002	100				
LOW THRUST SPIRAL MSN DESIGN	100713	70.200.34.5.4001	135				
S/C NAV OPTICAL CORRELATOR	100713	70.200.33.5.1001	200				
DDOR ERROR BUDGET DETERMINATION	100713	70.200.33.5.0001	150				
IN-ORBIT TESTBED FOR MARS N/W	100713	70.200.33.5.0002	225				
S/W RECONFIG. RADIO ADV DEV	100713	70.200.33.5.2001	165				
TOTAL			1375	0	0	0	0

OTHER INFORMATION:

Please refer to the individual task plans for detailed information on partnering, infusion plans, commercialization potential/plans, and reporting plans.