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1 Project Description

1.1 Introduction

This project proposes a multi-disciplinary effort to help develop new methods and technologies needed to conduct proximity operations at Near Earth Asteroids (NEAs) for use with both robotic and human (or combined) exploration missions. Another objective of this proposal is to build the infrastructure needed for New Mexico to become nationally competitive for funding in the fields of astrodynamics, Guidance, Navigation, and Control (GNC), telemetry and communications, orbital mechanics and orbit determination, and spacecraft attitude dynamics and estimation. The project goals are tied to NASA's Exploration Systems Mission Directorate (ESMD) and Science Mission Directorate (SMD) along with recent efforts to develop capabilities for future missions to NEAs. The importance of these research areas is reflected in the Review of U.S. Human Space Flight Plans Committee's 2009 "Flexible Path" alternative for human space exploration which was adopted by the current administration and in the number and importance of current and proposed robotic missions to small bodies. This NASA EPSCoR proposal leverages the engineering and scientific talent within New Mexico and a neighboring state by forming a partnership between engineers from New Mexico State University, the University of Colorado at Boulder, and the Air Force Research Laboratory, and an astronomer at New Mexico Tech. Our NASA center partner is the Jet Propulsion Laboratory.

Recently there has been much interest in sending robotic precursor missions to NEAs for scientific study and to prepare for a possible manned mission in the mid-2020s. Increased understanding of these small irregularly-shaped bodies is essential to any NEA deflection strategy implemented for planetary protection. In the future, NEAs could serve as fueling stations, mining sites, or remote observatories. Interest in asteroid exploration is demonstrated by recent, current, and proposed missions such as NEAR Shoemaker, Hayabusa, DAWN, OSIRIS REx, and BASiX. This investigation will be supported with numerical modeling including the use of JPL software using models of asteroids which are likely mission destinations. In addition to NEAs, many of the proposed strategies will also apply to missions to other solar system bodies such as comets and small planetary satellites. The Etscorn Campus Observatory at New Mexico Tech will be leveraged to obtain data for use in the asteroid modeling and simulations.

1.2 Project Purpose

The proposed research addresses an area of cooperative partnership between ESMD and SMD and contributes in significant ways to the R&D priorities of these divisions as well as to the research infrastructure, science and technology capabilities, higher education, and economic development of New Mexico. Within the 2010 U.S. National Space Policy are found the primary directives "*Maintain a sustained robotic presence in the solar system to conduct scientific investigations of other planetary bodies; demonstrate new technologies; and scout locations for future human missions*" and "*Pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet and to identify potentially resource-rich planetary objects*." The second of these is a Near Earth Objectives Observation (NEOO) program objective. The proposed work is aligned with priorities of ESMD's Advanced Capabilities Division (ACD) and Exploration Technology

Development Program (ETDP), which provides technology that will enable future exploration missions such as the new Exploration Precursor Robotic Missions. An asteroid sample return mission (OSIRIS REx) is one of three possible New Frontiers class missions to be selected this year for a 2018 launch, and BASiX is a proposed Discovery mission to a binary asteroid system.

In 2003 the State of New Mexico determined it was of critical importance to establish an Aerospace Engineering (AE) program in the state to enhance future economic development and for academic and research competitiveness. For this purpose state funds were appropriated at the level of $486,000 in recurring funds, to be used by NMSU and NMTech to develop an undergraduate AE degree program at NMSU (the only degree-granting AE program in NM and west Texas) and an undergraduate option in AE at NMTech. The first AE courses at NMSU were offered during the 2006/2007 academic year. Graduate AE degree programs (MS and PhD) received approval a year ago and the first AE graduate courses are currently being offered on campus and through distance course delivery, which the NM Space Grant Consortium (NMSGC) has been a partner is funding. NMSGC has also funded co-Is Butcher and Sanyal to develop new astronautics courses in the undergraduate AE program. The proposed research program will be critical in providing a platform from which to launch the graduate AE program and build research infrastructure in engineering and the space sciences in NM. In addition, the project leverages the unique astronomical capabilities at NMTech in the form of the Etscorn Campus Observatory which is dedicated to asteroid follow-up characterization studies, and provides a unique opportunity for engineering and science collaborative research on NEA environments.

1.3 Goals and Objectives

<u>Three major research goals include</u>:

- <u>Goal 1</u>: Develop strategies to plan trajectories and maneuvers of single or multiple spacecraft to enable NEA missions, including approach and orbital operations, descent, landing and surface operations, and autonomous guidance, navigation, and control capabilities.
- <u>Goal 2</u>: Study the impacts of communications and networking constraints within the framework of various protocols on NEA missions, and how such constraints affect and are affected by the trajectories of a constellation of spacecraft at a NEA system.
- <u>Goal 3</u>: Improve the gravity field modeling of select NEAs through new observations and the development of numerical modeling algorithms, for the purpose of more effective proximity operation modeling and design for robotic and human NEA mission targets.

<u>Specific NASA EPSCoR goals addressed by our efforts include</u>:

- <u>Goal 1</u>: Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while assessing and leveraging the many existing core capabilities relative to NASA in the state.
- <u>Goal 2</u>: Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program in space and aerospace related STEM-related research.
- <u>Goal 3</u>: Develop partnerships between NASA research assets and New Mexico academic institutions, federal laboratories, and industry.
- <u>Goal 4</u>: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.
- <u>Goal 5</u>: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for STEM education in New Mexico.

1.4 Proposed Research

1.4.1 Asteroid Missions: Past, Present, and Future

Although there are about 100,000 known asteroids including over 7,000 known NEAs (defined as those asteroids which have orbits that bring them within 1.3 AU of the Earth's orbit) [1], a total of only ten asteroid systems have been visited by spacecraft thus far. These include 951 Gaspra and the binary system 243 Ida (both observed by the Galileo spacecraft on its way to Jupiter in 1991 and 1993), 253 Mathilde (observed by NEAR Shoemaker in 1997), 9969 Braille (observed by Deep Space One in 1999), 2685 Masursky (observed by Cassini on its way to Saturn in 2000), 433 Eros (the first asteroid to be orbited and landed on, by NEAR Shoemaker in 2000-2001), 5535 Annefrank (observed by Stardust in 2002), 25143 Itokawa (hovered at and landed on by JAXA's Hayabusa in 2005), and asteroids 2867 Steins and 21 Lutetia (both observed during flybys of the ESA Rosetta spacecraft in 2008 and 2010). Only NEAs Eros and Itokawa were mapped completely and landed on. The WISE spacecraft recently completed its secondary mission (NEOWISE) and added 134 new near Earth objects to the known list [2].

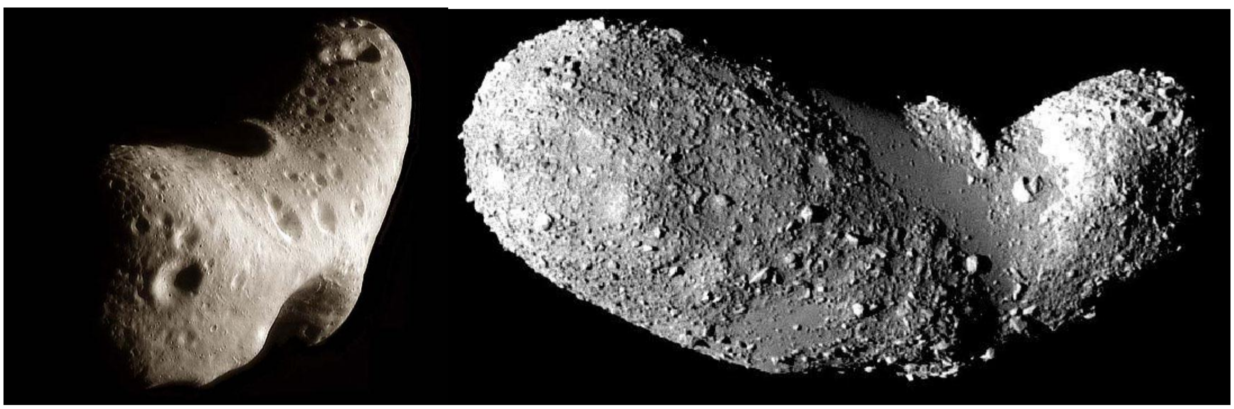

Figure 1: *Near Earth Asteroids 433 Eros (as imaged by the NEAR Shoemaker probe) and 25143 Itokawa (as imaged by the Hayabusa probe). The 630 m long Itokawa is one of the Apollo asteroids, whose orbits cross that of the Earth, despite having orbital semi-major axes larger than that of the Earth. Eros, the first discovered NEA, is a Mars-crossing asteroid with a maximum diameter greater than 10 km and a rotation period of 5.27 hours.*

Currently, NASA's DAWN spacecraft is scheduled to visit the asteroid 4 Vesta in 2011-2012 before continuing to the dwarf planet Ceres. DAWN will be the first spacecraft to enter orbit about a celestial body, study it, and then proceed under powered flight to another celestial body. The DAWN mission's encounter with Vesta will test new trajectory design strategies and provide important data on orbital stability and navigation that can be used in later asteroid missions. A number of robotic asteroid mission conceptual designs have been made, including missions to one NEA – 99942 Apophis – in particular. In 2029 Apophis will pass within geosynchronous orbital radius with a small possibility of passing through a "gravitational keyhole" that would set up a future impact on April 13, 2036 [3]. While Apophis broke the highest level record on the Torino impact hazard scale in 2004, the chance of the 2036 impact has been lowered to less than one in 250,000 [4]. The 2029 flyby is expected to significantly effect Apophis' trajectory and rotation [5]. Recently the Planetary Society sponsored a competition to design a robotic mission to Apophis and received several mission designs by corporations and student groups [6]. In 2009 the Review of U.S. Human Space Flight Plans Committee, in association with their "Flexible Path" exploration strategy option, requested a survey of known asteroids be conducted with the objective of identifying NEAs accessible for human exploration [7]. This strategy favors new destinations beyond low Earth orbit such as lunar orbit, libration points, NEAs, and eventually Mars orbit. Under this plan NEAs will be the primary previously-unvisited extraterrestrial surfaces on which humans can land. A survey resulted in a list of 36 NEAs with 58 opportunities for visitation between 2020 and 2050 [8].

Missions to small-bodies have a number of inherent difficulties relative to traditional space missions, particularly if touchdown or sampling maneuvers are included. The gravity of an asteroid is generally insufficient to pull the mass into a spheroidal shape. This results in highly irregular shapes and corresponding arbitrary gravitational fields which complicate the spacecraft dynamics increasingly with proximity. The modeling issues that must be dealt with to accurately describe the dynamics are numerous, and include accounting for and computing attraction from a distended, highly non-spherical body that may be tumbling in space, small perturbations from tidal forces and solar radiation pressure – which can be sufficient to strip a spacecraft out of orbit, and dealing with an unknown dust environment in proximity to the body. These difficulties are compounded when the navigation of a spacecraft in this environment must also be considered, as uncertainties in the gravity field, spin state, and non-gravitational forces acting on the spacecraft compound the already unstable dynamics. Accurate small body bulk density estimates are virtually impossible to obtain prior to arrival and shape estimates obtained from Earth-bound radar observations have limited resolution. Adding to these complexities is the fact that the spacecraft orbital and attitude dynamics have comparable energies. Therefore, translational-rotational dynamical coupling can cause transfer of energy between these modes of motion. In addition, the weak interaction between the spacecraft and asteroid may alter these dynamics over long time scales, particularly in regions associated with resonances between the orbital period and the asteroid's rotation period [9]. Finally, the large travel time for signals to Earth makes complete Earth-based navigation impractical. Hence, the ability of the spacecraft to respond to its environment must be pre-planned or must be implementable using on-board autonomy – ideally with a rational distribution of functionality between these two extremes.

Over the past 10-15 years the natural and controlled dynamics of particles and space vehicles in the asteroid environment have been studied [10-14]. Also, the basic understanding of gravity field computation and non-gravitational modeling in these environments are well understood [15-18]. Additionally, the dynamics of a space vehicle under controlled motion has also been investigated, although not to as great of a degree [19-21]. Nevertheless, there are still specific issues that must be addressed for the future implementation of space vehicle exploration at a small body. Much of the prior work considers only the translational (orbital) motion of the spacecraft modeled as a point mass. In this regard, the dynamical modeling in [22] of the coupled attitude and translational motion of the spacecraft and the small body is a notable exception. However, a robust treatment of guidance, navigation and control with a comprehensive model of the dynamics and uncertainties due to gravity and solar radiation has not been attempted yet. Besides gravity, solar radiation forces can cause appreciable forces and torques on small solar system bodies due to the Yarkovsky and YORP effects [23].

The research team plans to blend the unique NEA operations knowledge of co-I Scheeres gained through the NEAR and Hayabusa missions with the specialized expertise of co-I Sanyal in guidance, navigation, and control, of co-I Creusere in telemetry and space communications, and of the AFRL collaborators in proximity operations and navigation to develop mission planning tools for asteroid orbit, approach and landing. While the individual aspects of this mission planning effort are well developed for other applications, they have not been integrated into a systems level approach tailored for asteroid applications. In the following sections, our proposed approach to these problems will be summarized in five categories: 1) approach to asteroid and orbital operations; 2) descent, landing, and surface operations; 3) telemetry and communications; 4) guidance, navigation, and control; and 5) asteroid observation and modeling.

1.4.2 Approach to Asteroid and Orbital Operations

The first phase of a NEA mission design includes the choice of the specific trajectory used from Earth to the asteroid. This also includes the return trip in the case of either a sample-return or human mission. Initial research into mission design strategies for robotic asteroid missions that are precursor to potential human missions [24] and techniques and capabilities required for human NEA missions [25] have recently been conducted. Two strategies for human NEA missions that have recently been suggested include the use of solar electric propulsion (SEP) to provide the capability to implement a wider variety of missions with low injected mass to low Earth orbit [26] and lunar flybys to reach asteroids that are otherwise inaccessible due to constrained launch capability [27]. In this project we will further investigate these strategies and others for NEA missions.

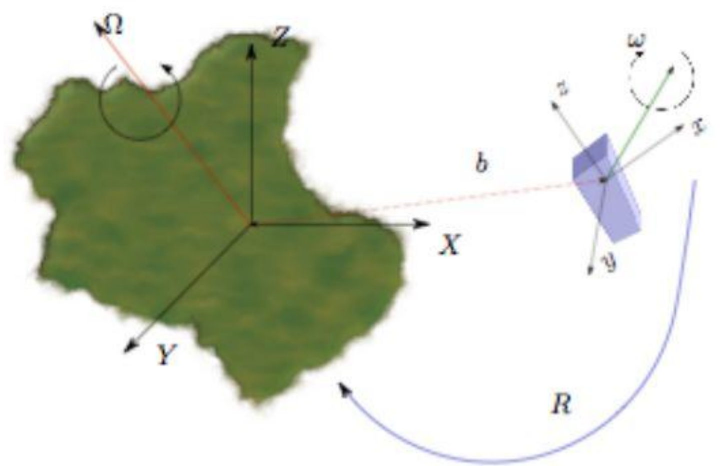

Figure 2: *The configuration of the spacecraft (blue) with respect to an asteroid (green) is given by the relative position vector **b** of the center of mass with respect to an asteroid-fixed coordinate frame XYZ, and the relative orientation **R** of the spacecraft-fixed coordinate frame xyz with respect to frame XYZ. The asteroid rotates about the axis shown with angular velocity **Ω** while **ω** is the spacecraft's angular velocity relative to the asteroid.*

For studying the orbital dynamics about NEAs, we will model the spacecraft as a rigid body in space, with its motion influenced by the gravity of the asteroid as well as the Sun's gravity. We assume that the resultant force and torque on the spacecraft due to these uncertain external effects and their time rates of change have known bounds determined from astronomical observations [28]. The motion of the spacecraft at any given instant is specified by its configuration variables, which describe the position and attitude with respect to an asteroid-fixed coordinate frame, and its velocity variables, which describe its translational and rotational velocity with respect to the asteroid-fixed coordinate frame. These state variables are shown in Fig. 2. The dynamics model for the spacecraft to be used is similar to that used to obtain a robust and almost global attitude feedback-tracking controller in [29], the attitude estimation scheme in [30-31], and for the inertia-free adaptive attitude tracking control scheme in [32]. In conjunction with modeling the orbital mechanics, the required maneuvers to be studied include stabilization of the relative spacecraft motion about the asteroid [22] and hovering over the surface [19-21].

1.4.3 Descent, Landing, and Surface Operations

For surface exploration and NEA sample return missions, it is necessary to perform descent and either soft landing or "Touch-And-Go" (TAG). The descent problem was studied inhouse by NASA in [33]. However there remains a lack of analysis of the end-to-end dynamics and control of these landing maneuvers that adequately accounts for navigation, guidance and control loops acting in a general fashion. Crucial questions – for example the utility of stereoscopic vision vs. lidar altimetry – can lead to very different operations plans and strategies and have significantly different costs, yet have not been studied in detail. TAG trajectory designs typically include four main phases: staging, descent, contact, and ascent [34]. The designs for these phases are driven by engineering and science constraints and the small body environment. For example, for fast rotators the Coriolis and centripetal accelerations can dominate gravitational effects close into the body. "Push-down" and corridor correction maneuvers may need to be designed into the descent sequence, while issues such as landing site location, plume infringement minimization, and contamination requirements may present design constraints.

The Hayabusa spacecraft visited asteroid Itokawa in the Fall of 2005. During its stay at the asteroid it did not enter orbit about that body but implemented "inertial hovering" within a specified bounding box for the majority of its stay there. At several points during the mission it attempted landings on the surface of the asteroid. These landing attempts consisted of transitioning the spacecraft from a hovering location to a close proximity location from which it could place itself into the asteroid rotating frame and descend to the surface to sample it. The operations team (which included co-I Scheeres) actually tried several different approaches to this maneuver unsuccessfully. Finally, they were able to implement an entirely successful approach to the surface [35-36] that essentially coupled ground-based operations in a quasi-closed loop system with the limited on-board autonomy of the spacecraft. While successful, such an approach is not robust and would most likely not survive the NASA review process.

We propose to develop integrated simulations of the 6-DOF motion as the spacecraft approaches the surface of an asteroid to evaluate the performance and ability of different proposed navigation suites to transition into descent and landing trajectories. To ensure realism the highest fidelity asteroid models will be used in the simulations to drive navigation sensor models. In addition, the fully coupled rotational and translational motion of the spacecraft will be modeled. For landing on binary system asteroids a strategy proposed in [37] which involved "shooting" a lander from an orbiter through the L_2 libration point gateway to the smaller of the binary pair will be studied in further detail. Such a lander may bounce repeatedly and roll on the asteroid surface. The likely path of this "bounce-and-roll" could possibly be mapped based on contact/impact mechanics and the rotational dynamics of the smaller asteroid.

Controlled robotic probes that descend from a parent spacecraft and hop from point to point on the asteroid surface for exploration and sample collection were proposed in the last decade [38-40]. The original intention of the Hayabusa mission was for the parent spacecraft to send a probe (MINERVA) directed at the asteroid's surface. However, this probe failed to land on the surface due to deployment errors when the spacecraft unintentionally entered "safe mode". One can also envision interesting concepts such as robotic surface probes hopping back and forth between bodies of a binary system, or for a constellation of orbiters to provide navigation capabilities for any surface probes in a manner similar to GPS. Such concepts will also be investigated for their practicality in the exploration of specific asteroid systems.

1.4.4 Telemetry and Communications

Adding to the dynamical complexities of NEA missions are the issues involving communications of multiple spacecraft and/or surface probes that operate in a coordinated fashion. Due to the line of sight requirement at most RF frequencies, it is necessary that some of the space-based probes act as relays. This adds another constraint to the problem of automated orbital platform control: the sensing mission of the platform must now be accomplished despite the gravitational variability discussed previously while at the same time guaranteeing that the *ad hoc* network connecting all of the sensors remains intact. It should be noted that to communicate the collected data back to Earth, one of the platforms would generally be tasked as the relay.

Over the past 50 years, the problem of communicating with deep space unmanned probes has been thoroughly studied. In particular, the problem of transferring information from Earth-based controllers to the probe and back has been effectively and efficiently solved. More recent research has instead focused on the problem of information networking between multiple space-based platforms operating in relatively close proximity to one another. Many general studies of network architectures and physical layer communications issues have been published over the years [41-46]. Most of the detailed studies have focused on either earth-orbit communications [47-48] or Moon/Mars communications [49-51]. There have also been a number of recent papers focused on missions to asteroids [52-53], but none of these study the local network communication issues in the detailed manner proposed here: specifically, they do not consider the problem of maintaining network interconnectivity between multiple autonomous or semi-autonomous sensing platforms as a mission constraint. To our knowledge, this issue has not been addressed in the literature published to date.

It is the contention of the authors of most of the papers cited above that advances in robotic and micro-sensor technologies will likely lead to a major paradigm shift in the design of future missions in which multiple robotic sensor platforms are deployed in the vicinity of a target object. Some of these sensor platforms might be surface-based while others will be space-based, and the collected data would be relayed back to earth through a single deep space communication link residing on one of the platforms. To aggregate this data, some sensing platforms may need to be used as intermediate relays The communication constraints will strongly impact both the hardware design and the mission planning, and our goal is to incorporate it into the simulation framework that is being developed in this project.

We will use two complementary strategies to approach the issue of communication or networking protocols. The first will be a generic strategy that is independent of the underlying communications technology—one might call this an information-theoretic strategy. The other will be a detailed, packet-level simulation strategy. The first will be especially useful in developing the communications specifications for the various robotic platforms that comprise the mission while the latter will support detailed mission planning of the completed system. Another focus will be combining a detailed simulation of the communication system with the spacecraft simulations being designed by other members of the team. For these detailed simulations, we model the data production of each sensor on each individual platform, and we simulate the communication network down to the packet level using the public domain ns2 software in which a wide variety of stochastic channel models can be applied, allowing us to easily incorporate models that have been validated for space communications into our simulations.

1.4.5 Guidance, Navigation, and Control

The motion estimation scheme in [30-31] will be extended in this research to also estimate the uncertain external inputs between measurement intervals. These estimates will then be used in a feedback control scheme to robustly control the spacecraft to follow a desired trajectory with respect to the asteroid. This control scheme will be similar to the robust control schemes appearing in [29,32,54] with a guaranteed large domain of convergence. The navigation algorithm for the spacecraft will be based on a geometric variational integration scheme for motion state prediction, combined with a deterministic filtering scheme for updating state estimates based on the measurements. Propagation of states between discrete measurements will be carried out using Lie group variational integrators, which preserve the geometry of the state space of motion. These integrators have been used for state estimation in [30,55], and for numerical simulation of control schemes in [31,54]. A filtering update scheme, based upon set-bounded uncertainties on measurements and external inputs like those in [30-31,56], will be used to update state estimates. Unlike the extended Kalman filter, this scheme will be robust to the probability distributions of the measurement noise and uncertain external inputs, and it will also update estimates of the uncertain external inputs on the spacecraft based on the updated states.

Desired motion trajectories for orbiting the asteroid or landing on it will be obtained by applying a receding horizon optimal control scheme. Receding horizon optimal guidance based on linearization has been used for astrodynamics problems, e.g. [57]. However, in this research, we will obtain a desired trajectory with nonlinear receding horizon optimal control scheme based on the nonlinear dynamics model, using Pontryagin's minimum principle. This guidance scheme will be solved offline numerically over a finite time horizon starting from the current time, to obtain a desired state trajectory in a time interval. A feedback tracking control scheme that exhibits almost global tracking convergence will be used to robustly control the trajectory so that it follows the desired state trajectory in the presence of the uncertain external inputs.

1.4.6 Asteroid Observation and Modeling

For orbital motion about small bodies at medium to large distances it is sufficient to use a spherical harmonic expansion for the characterization of a small body's gravity field. This runs into problems as soon as the gravity field must be evaluated within the circumscribing sphere that encloses the asteroid, as the usual spherical harmonic expansion is divergent and cannot be used for modeling. Alternate approaches to this situation include the use of the closed-form gravitational potential for a polyhedral body, which does not suffer these divergence issues. The drawback is that this model assumes a constant density distribution, which was found for the asteroid Eros [58] but is not expected in general for other small bodies. A technique to evaluate and modify the internal density distribution using the polyhedral models has been developed in [59], but is limited since the form of the density distribution should be specified. The ideal approach would be to match the spherical harmonics gravity coefficients estimated outside of the circumscribing sphere with a polyhedral body gravity field representation at or near the surface. This approach for gravity field modeling has not been investigated but will be pursued here.

The NMTech co-I (Klinglesmith) will leverage the Etscorn Campus Observatory at New Mexico Tech, dedicated to NEA and other asteroid follow-up characterizations, to obtain observational data for use in the asteroid modeling and simulations. In order to obtain shape information for target asteroids, it will be necessary to use asteroid light curves at different phase angles to model the asteroid. The Etscorn Campus Observatory is a well equipped facility for obtaining asteroid light curves with three separate telescopes: two Celestron C-14s and a 6-inch Takahashi. All 3 telescopes are computer controlled and equipped with Santa Barbara Instrument Group CCD camera systems. They are capable of obtaining asteroid magnitudes to within a few percent accuracy down to 16th magnitude unfiltered [60-61]. R magnitudes would be limited to 14th magnitude. At least one C-14 would be available at all times for obtaining asteroid light curves. The second C-14 would be available when not being used for astronomy student labs. Co-I Klinglesmith and three students will collect and reduce the data for use in modeling the gravity fields of the observed asteroids by other team members.

1.5 Anticipated Results

The anticipated technical results of this project include obtaining an understanding of the spacecraft maneuvers required to enable robotic and human missions to NEAs, improving the gravity field modeling of small, arbitrarily-shaped bodies, new techniques for attitude control in the proximity of irregular bodies, and an increased understanding of how attitude dynamics are influenced by translational/rotational coupling in the NEA environment. Also, the control laws necessary to implement touchdown or TAG operations at the asteroid surface to support sample collection will be developed. These capabilities will assist future NASA asteroid exploration missions such as the proposed OSIRIS REx and BASiX asteroid missions. Furthermore, new numerical schemes will be designed that can accurately simulate the relative motion between an irregular asteroid and a spacecraft over long time periods and that can be used for propagation of states during navigation. A likely result of the proposed research is the development of advanced or improved navigation and timing capabilities in the vicinity of a small body, and autonomous close proximity operation capabilities. Such capabilities were highlighted in the RFPs for Technology Demonstration Mission proposals recently issued by NASA's Office of the Chief Technologist, and will be enabled in the proposed project through the synthesis of the astrodynamics and spaceflight dynamics expertise of co-Is Sanyal, Butcher, and Scheeres with the communications and telemetry expertise of co-I Creusere. Together with the use of asteroid astronomical observations by co-I Klinglesmith to support accurate NEA modeling, this blend of research expertise makes this project unique in advancing asteroid exploration technologies.

Particular attention will be paid to the integration of the research areas discussed above. The impact of success in this endeavor will be 1) the design in the final year of an end-to-end robotic sample return mission to an asteroid by a student/faculty team from each of the three universities with the goal of submitting the completed design to a competition similar to the recent Planetary Society Apophis Mission Design Competition, and 2) the development of a cradle to grave asteroid mission planning tool. The primary activities involved in this proposed effort will be the systematic sharing of asteroid mission challenges among the team and the subsequent development of tools encapsulating knowledge of each of the areas discussed above. Other impacts include strengthening research and educational programs in the new AE program, as well as the electrical engineering program, at NMSU, and the astronomy program at NMTech.

The goal of NASA EPSCoR is to provide seed funding that will enable jurisdictions to develop an academic research enterprise directed toward long-term, self-sustaining, nationally-competitive capabilities in aerospace and aerospace-related research areas of strategic importance to the NASA mission. NEA exploration has recently received elevated priority at NASA with several NEA precursor robotic missions tentatively planned in the coming years in preparation for an eventual manned mission to an asteroid. The research program, partnerships, and NASA interactions which have been discussed will not only help to establish New Mexico institutions as major players in a topic of major importance in the current administration's space policy and in the space sciences in general, but will also help to develop the research infrastructure of the new AE program at NMSU, to improve the capabilities of New Mexico universities to gain support from sources outside the NASA EPSCoR program, to develop partnerships with NASA research assets, other academic institutions, and industry, to contribute to the overall science and technology capabilities, higher education, and economic development of the state, and to improve the environment for STEM education in the state of New Mexico.

1.6 Existing Research

The New Mexico NASA EPSCoR program was established in May 2007, and there are currently four other investigations in the state being funded through this program: Structural Health Monitoring and Self-Healing of Aerospace Structures, New Mexico Exoplanet Spectroscopic Survey Instrument, New Mexico Solar and Stellar Seismology, and Infrared Instrument Development for In-Situ Organic Detection. Two projects have end dates in Fall 2011, while the remaining two are tied to the Science Mission Directorate (SMD). None of these four projects are fundamentally tied to the Exploration Systems Mission Directorate (ESMD). Our proposed investigation, which is closely linked with goals and objectives of both ESMD and SMD, is an engineering project with a supporting scientific component and thus is distinct from the existing NASA EPSCoR awards in New Mexico and represents a new direction for the jurisdiction. NASA EPSCoR programs that address both engineering and science will give the state of New Mexico a broader context for developing capabilities relevant for NASA.

Although this proposal represents an important new challenge in the form of establishing research expertise in New Mexico in the field of proximity operations around NEAs and asteroid modeling, the research team as a whole has significant expertise and prior research experience in these areas (i.e. co-I Scheeres) as well as in the general areas of spacecraft guidance, navigation, and control (i.e. co-I Sanyal), and telemetry and communications (i.e. co-I Creusere). Significant experience in these areas also exists at the Air Force Research Laboratory in Albuquerque (i.e. collaborators Jah and Lovell), and through AFRL's Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA). There is also a recently funded research project in the areas of astrodynamics within the NMSU aerospace engineering program, with more proposals currently under review. In particular, Co-I Butcher has recently been awarded a $563,860 grant from DoD for research related to libration point orbits, and he recently teamed with co-I Sanyal on a proposal to NSF dealing with attitude estimation and control in unmanned vehicles including spacecraft. In addition, a whitepaper was recently submitted to AFRL's solicitation on resident space object characterization. It should be noted that, while expertise in space dynamics is a new focus in engineering at NMSU, the department, engineering college, university, and the State of New Mexico have committed to building up this area, as is apparent from the state's commitment to funding the new aerospace program, the recent hiring of co-I Sanyal, the support from NM Space Grant for new course development in astronautics, and the recently funding one of co-I Butcher's Ph.D. students by NMSU to do research in astrodynamics.

In astronomy New Mexico has a tradition of excellence with well-known observatories located throughout the state. In addition, co-I Creusere's research specialty in communications and telemetry is especially strong in the Electrical and Computer Engineering department at NMSU (one of only six universities designated as Telemetering Centers of Excellence by the International Foundation of Telemetering), and Creusere holds the Frank Carden Chair in Telemetering and Telecommunications. Finally, the experience of co-I Scheeres in asteroid modeling and spacecraft dynamics around small bodies will be an invaluable part of the project, and his participation will help to build expertise in this area in New Mexico. Both co-I Scheeres and collaborator Jah have prior experience on real robotic asteroid missions (NEAR and Hayabusa), while co-I Scheeres is a Science Co-I on the NASA OSIRIS REx New Frontiers asteroid sample-return mission proposal and the PI on the NASA BASiX Discovery mission proposal to deploy seismometers on the surfaces of the binary asteroid system 65803 Didymos.

1.7 NASA Alignment and Partnerships

1.7.1 Relevance to NASA and Jurisdiction

The relevance of the proposed research to the strategic goals of NASA and of ESMD and SMD in particular was previously described in Sections 1.1-1.3. The FY'11 NASA EPSCoR Cooperative Agreement Notice lists "Robotic Systems for Precursor NEA Missions" as a major topic of interest and describes: "*Navigation and proximity operations systems; techniques for interacting and anchoring with NEAs; methods of remote and interactive characterization of NEA environments;…spacecraft autonomy*." The recent NASA authorization law resulted in two new ESMD Exploration Study Teams directly relevant to the proposed topic: Flagship Technology Demonstrations and Exploration Precursor Robotic Missions.

Within New Mexico there is a strong commitment to the strengthening of science, technology, and economic capabilities that are aligned with NASA's goals and objectives. In 2003, former Governor Richardson outlined an economic growth package that included making NM "a national leader for advanced technology". In 2005, the 21st Century Space and Aerospace Cluster was established as one of five interdisciplinary research clusters on the NMSU campus. The mission of the Cluster is to "form a mutually supportive group of educators, researchers, and practitioners to advance 21st century space-related opportunities for research, teaching, and economic development at NMSU and in the region." The research proposed herein provides an opportunity for the development of new technological capabilities and an educational and training program for the development of the future workforce within the state of New Mexico. Due to strong interest from students and working professionals in southern New Mexico (e.g. Holloman AFB, White Sands, Spaceport America, etc.), beginning in Fall 2011 a space dynamics track and certificate program will be created in the new graduate AE program with new courses to be taught in Astrodynamics, Spacecraft Attitude Dynamics and Control, and Statistical Orbit Determination (to be taught by co-Is Butcher and Sanyal) along with a course in Space Weather taught by another MAE faculty member. University and departmental commitment to this area is evident from the recent hiring of a new AE faculty in space dynamics, co-I Sanyal. Aerospace laboratories to be created include a virtual reality laboratory for education and research in orbital mechanics and an educational site license for STK software.

1.7.2 Partnerships and Sustainability

The proposed research is a collaboration between New Mexico State University, New Mexico Tech, and the University of Colorado at Boulder. Furthermore, two engineering departments at NMSU (Mechanical/Aerospace and Electrical/Computer) are represented. Future collaboration with University of New Mexico researchers, especially in graduate education and associated research, is expected as the proposed program develops and is extended through funding from other sources. During the period of performance the research team will collaborate with the Drs. Moriba Jah and Thomas Alan Lovell at the Air Force Research Laboratory, Space Vehicle Directorate. The joint NMSU/NMT/CU/AFRL research program will enhance the overall stature of astrodynamics and asteroid observational astronomy in New Mexico.

Co-I Butcher recently finalized a formal relationship between NMSU and the Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA), a multi-university consortium for astrodynamics research (of which CU is also a member) directed by Dr. Moriba Jah of AFRL, which will lead to additional long-term funding in astrodynamics and space-related research. (NMSU is the only ASTRIA university in New Mexico.) The partnership with

AFRL/ASTRIA has also resulted in the Orbital Mechanics course at NMSU being taught this semester by Dr. Thomas Alan Lovell of AFRL (It is usually taught by co-Is Butcher and Sanyal.) Other than the valuable research expertise of co-I Scheeres in the proposed research, the focus of the partnership with CU Boulder will also include the utilization of their engineering distance education program, the Center for Advanced Engineering and Technology Education (CAETE), for training NMSU students in advanced areas of astrodynamics and spacecraft navigation. The CU CAETE program, through the CU Aerospace Engineering Sciences Department, offers an unusually large variety of online classes in areas such as Optimal Spacecraft Guidance and Control, Advanced Astrodynamics and Celestial Mechanics, Advanced Statistical Orbit Determination, and Advanced Spacecraft Attitude Dynamics and Control, which contain more in-depth content than the graduate AE courses currently being initiated at NMSU, while still being directly relevant to the proposed research.

The sustainability of the work beyond the three-year project proposed here is vital to national research competitiveness as measured by publication in top journals (with attendant citations), production of Ph.D. graduates that can compete with graduates of top universities for government laboratory and academic positions, and the ability to compete with all comers in the competitive NASA funding programs. To support the sustainability of the work and to help develop a long-term strategy for continued funding in this area, current collaborations with researchers in New Mexico and Colorado at NMSU, AFRL, LANL, Sandia, CU Boulder, and other New Mexico universities, especially in graduate education and associated research, will be broadened and solidified as the proposed program develops and is extended through funding from other sources. The proposed research will enhance the overall stature of engineering and space-related research in the state of New Mexico, while at the same time developing new research and operational capabilities in support of NASA's space exploration and science goals.

Specifically, the following plans will move New Mexico to research competitiveness:

- Develop a statewide Research Center in astrodynamics, spacecraft navigation, orbit determination and related areas. NMSU and AFRL have agreed in principle to launch this initiative; NMTech and UNM are likely partners. This Center will be organized during years 1-2, with the plan of completing joint research projects and competing for funds by years 2-3. A main goal will be to establish New Mexico as a national leader in these areas of research.
- Use the aforementioned Research Center as a primary focus for development of a NSF Integrative Graduate Education and Research Traineeship (IGERT) program in the general area of spacecraft navigation, orbit determination, proximity operations, rendezvous, and docking. The objective of this program would be to educate PhD students in diverse technical areas, enabling them to function broadly and deeply in the research arena. The goal would be to prepare for this IGERT grant during year 1 and to propose during years 2-3.

1.7.3 NASA Interactions

One team member, co-I Scheeres, has extensive experience collaborating with NASA scientists and engineers on multiple funded projects related to the proposed research. Future collaborations of the research team with NASA personnel will be fostered in the area of asteroid orbital environments, approach, and landing. To better fit within NASA priorities, it was recommended to have close collaboration with Dr. Shyam Bhaskaran – an expert in mission design and navigation around small bodies. Preliminary interaction with the JPL research staff below will lead to future collaborations in which the proposed methodologies will complement existing NASA/JPL efforts in modeling proximity operations for asteroid exploration missions.

Names and titles of NASA researchers with whom proposers will collaborate:
Dr. Shyam Bhaskaran, Supervisor - Outer Planets Navigation Group, NASA JPL, Section 343 Mission Design and Navigation, Pasadena, CA (818-354-3152).
Dr. Jon Sims, Supervisor – Outer Planets Mission Analysis Group, NASA JPL, Section 343 Mission Design and Navigation, Pasadena, CA (818-354-0313)
Dr. Jeff Parker, Mission Design Specialist, NASA JPL, Org. 343D Inner Planets Mission Analysis, Pasadena, CA (818-393-6675).
Dr. Brent Buffington, Aerospace Engineer, NASA JPL, Org. 343M Outer Planets Mission Analysis, Pasadena, CA (818-393-7964)
Mr. Mark Wallace, Mission Design Engineer, NASA JPL, Sec. 343 Mission Design and Navigation, Pasadena CA (818-354-4236)

Co-I Butcher recently visited NASA/JPL and discussed this proposal topic with each of these NASA personnel. He received positive feedback on the research ideas expressed in this proposal. The JPL collaborators will function as technical advisors for the project, reviewing progress and guiding research efforts through participation in biannual video conferences that include presentations by the project co-Is. Also, co-I Butcher will spend at least two summers working at JPL and utilizing JPL facilities and mission design software for this research.

1.7.4 Diversity and Outreach

The broader impacts of the proposal include a dynamic partnership between the three universities, NASA, and AFRL that will give students real-world training and facilitate technology transfer. The primary mechanisms to increase the number of degrees awarded to minority students at NMSU, a Hispanic serving university and Minority Serving Institution (MSI) as classified by NSF, will be collaborations with the New Mexico Alliance for Minority Participation (NM-AMP – see attached letter of support), the Society of Hispanic Engineers, and NMSU Engineers Without Borders to identify students from under-represented groups with compatible interest. Co-Is Butcher and Sanyal have both worked over the years with NM-AMP, which is directed by Dean of Engineering and Regents Professor Ricardo B. Jacquez. (The NMSU College of Engineering has 42% Hispanic student enrollment, 4% Native American enrollment, and 2% African American student enrollment according to 2009 statistics.) It is noted that NMSU and the Universidad Autonoma de Chihuahua (UACH) recently began offering a joint B.S. degree program in aerospace engineering in which 30-40 UACH students complete their last three semesters at NMSU and receive AE degrees from both institutions. Diversity of the NMSU engineering student body is also evident in both the AIAA student chapter and the NASA student micro-gravity team, both of which are lead by minority student officers. Students with disabilities will be recruited through the NMSU RASEM (Regional Alliance for Science, Engineering, and Mathematics) program, which has a strong track record recruiting disabled students. The Society of Women Engineers, Women in Science, and the Hypatia Institute at New Mexico Tech and the University of Colorado will also be utilized to involve female and minority engineering and astronomy students in the proposed research activities. The results from the research will be disseminated through publications, conference presentations, classroom teaching, the internet, and, in a manner appropriate to the audience, to young people through various outreach activities. The engineering and astronomy programs will be utilized to interest New Mexico K-12 students in STEM disciplines and space-related careers in particular. The local Students for the Exploration and Development of Space (SEDS) chapter will be visited to provide inspiration to students to pursue careers in space science areas.

1.8 Timeline

(S = lead by the co-Is at NMSU; T = lead by NM Tech co-I; C = lead by CU co-I).

Tasks	Year 1				Year 2				Year 3			
Initiate asteroid observation and gravity modeling, **with integration of the observation data into asteroid gravity models**	T	T	C	C								
Assess asteroid approach trajectories including SEP and lunar flyby	S	S	S	S								
Develop new courses for space dynamics track in NMSU MAE dept.	S	S	S	S								
Initiate educational outreach program	S	S	T	T								
Write annual report and report to JPL staff on program progress				S								
Begin work on guidance schemes for descent and landing on asteroids					C	C	C	C				
Begin navigation and motion estimation in asteroid environment					S	S	S	S				
Begin communications and telemetry studies, **and integrate communications constraints into orbital and proximity operations**					S	S	S	S				
Continue work in asteroid observation and modeling					T	T	C	C				
Develop a statewide Research Center for Astrodynamics Research					S	S	T	T				
Write annual report and report to JPL staff on program progress								S				
Expand year 2 descent and landing studies to include feedback control strategies for surface rendezvous and TAG operations									C	C	C	C
Expand year 2 work on telemetry studies to include communications constraints on an array of orbiting platforms and landers									S	S	S	S
Continue work on navigation and motion estimation, and initiate work on guidance schemes for asteroid landing and departure									S	S	S	S
Synthesize areas developed into a student/faculty robotic asteroid sample return mission design and submit to a design competition									S	S	C	C
Design a cradle-to-grave asteroid mission planning software tool that incorporates asteroid approach, orbital, descent, landing, and surface operations, GNC, telemetry, and asteroid modeling									C	C	S	S
Document results from educational outreach program									T	T	T	T
Write proposal for NSF IGERT to obtain funds for continued work									S	S	S	S
Write final project report and report to JPL staff on program progress											S	S

1.9 Management and Evaluation

1.9.1 Results of Prior NASA EPSCoR Research Support

New Mexico NASA EPSCoR has four currently active research programs (see Section 1.6). None of the four programs have been completed. Current EPSCoR research has resulted in 32 journal papers, 49 conference presentations, and $4,676,000 in additional research dollars.

New Mexico NASA EPSCoR received seven pre-proposals for this opportunity. All members of the New Mexico Technical Advisory Committee (NM-TAC) were contacted by the NM EPSCoR Director and invited to participate in the selection of proposals to go forward. NM-TAC reviewed the submitted pre-proposals and selected two teams to write full proposals. This project was selected on Jan. 22, 2011 by the TAC to go to the full proposal for submission to NASA. The TAC then reviewed the full proposal, making recommendations for improvement. The involvement of the TAC in the development of this proposal increased its quality.

1.9.2 Personnel

Principal Investigator - Patricia C. Hynes, Director of the New Mexico NASA EPSCoR Program and Director of New Mexico Space Grant Consortium. She will be responsible for the overall administration of the effort as well as program evaluation and monitoring.

Co-Investigator/Science PI - Dr. Eric Butcher, Dwight and Aubrey Chapman Associate Professor, Mechanical and Aerospace Engineering, NMSU. His research expertise includes nonlinear dynamics and controls. He has taught orbital mechanics and spacecraft attitude dynamics/controls for the past 10 years, and was recently awarded the NMSU MAE Academy Professor of the Year Award and the University Research Council Early Career Award for Exceptional Achievements in Creative Scholarly Activity.

Co-Investigator - Dr. Amit Sanyal, Assistant Professor, Mechanical and Aerospace Engineering, NMSU. He has experience in spacecraft guidance, navigation, and control, and estimation theory.

Co-Investigator - Dr. Charles Creusere, Professor and Frank Carden Chair in Telemetering and Telecommunications, Electrical and Computer Engineering, NMSU. His expertise is in telemetry.

Co-Investigator - Dr. Dan Klinglesmith, Research Scientist, Etscorn Campus Observatory, NM Tech. Dr. Klinglesmith is an observational astronomer whose specialty is asteroid follow-up characterization.

Co-Investigator - Dr. Daniel Scheeres, Professor and A. Richard Seebass Chair, Aerospace Engineering Sciences, University of Colorado at Boulder. Dr. Scheeres' extensive experience includes spacecraft and orbital mechanics about asteroids and comets, asteroid threat mitigation issues, celestial mechanics of translational/rotational coupling, and modeling and dynamical evolution of comets and asteroids. He was on the science teams for both the NASA NEAR and JAXA Hayabusa missions to asteroids Eros and Itokawa. Main-belt asteroid 8887 Scheeres is named after him.

Collaborator – Dr. Moriba Jah, Director, Advanced Sciences and Technology Research Institute for Astrodynamics, Space Vehicle Directorate, AFRL. Dr. Jah is an expert in spacecraft navigation.

Collaborator - Dr. T. Alan Lovell, Director, Space Scholars Program, Space Vehicle Directorate, AFRL. Dr. Lovell's expertise is in formation flying, spacecraft relative motion, and optimal guidance.

Four graduate students and four undergraduate students at NMSU, NMTech, and CU will be supported by this research effort. All students supported by this funding will be U.S. citizens in an effort to build the technical workforce prepared to work for NASA and its contractors. New Mexico NASA EPSCoR is committed to supporting diversity and will encourage female, minorities and persons with disabilities to actively participate in the program.

NOTE: Dr. Sanyal is a U.S. Resident and will soon be eligible to apply for U.S. Citizenship. Dr. Sanyal has a tenure track faculty position at NMSU and plans to reside in NM. Dr. Sanyal's expertise in space guidance, navigation, estimation, and control is essential to the project.

1.9.3 Research Project Management

New Mexico EPSCoR will be managed through the New Mexico EPSCoR/Space Grant lead office at NMSU. Dr. Patricia C. Hynes, Director of NMSGC and NM NASA EPSCoR, will be responsible for the day-to-day management of the NASA EPSCoR program, including interactions among collaborating institutions, NASA Field Centers, and space and aerospace related industry**.** The New Mexico EPSCoR Director will work closely with the TAC to align our research focus to meet NASA and New Mexico research priorities. The EPSCoR office will be responsible for contract requirements including budgeting and reporting requirements. Co-Is Butcher and Scheeres will be responsible for interfaces with NASA/JPL as well as for the technical progress and research content. The proposed research tasks will be performed by the five co-I's and the AFRL collaborators as follows (managing investigators underlined):

- Approach to Asteroid and Orbital Operations: Scheeres, Sanyal, Butcher, Jah, Lovell
- Descent, Landing, and Surface Operations: Butcher, Scheeres, Creusere, Sanyal, Lovell
- Telemetry and Communications: Creusere, Sanyal, Scheeres
- Guidance, Navigation, and Control: Sanyal, Scheeres, Butcher, Jah
- Asteroid Observation and Modeling: Klinglesmith, Scheeres, Butcher

1.9.4 Project Evaluation

Evaluation is a key consideration not only in the demonstration of effectiveness of the program, but also in continuous improvement and program refinement. New Mexico EPSCoR Director Dr. Patricia Hynes has conducted extensive activities in assessment. She will design and implement the evaluation plan. Evaluation data will be collected from researchers each year as part of their report to NASA EPSCoR. The evaluation will allow us to monitor our progress and document benchmarks toward achievement of program goals and objectives. The evaluation will be both formative and summative. Formative evaluation will include an annual assessment of the proposed research metrics. Formative evaluation results will be brought to the NASA EPSCoR Technical Advisory Committee (TAC) for feedback and strategies to enhance program success. NASA collaborators will be involved in annual progress evaluations. Annually, we will be looking for faculty and research areas which show promise for additional funding. Summative evaluation will include a comparison of pre-award and post-award data analysis. Research faculty will involve undergraduate and graduate students in their research. This will not only contribute to workforce development in NASA research areas but encourage student retention. Students receiving $5,000 or more in support will be tracked through first employment. We will utilize the NASA OEPM system for longitudinal tracking of student participants.

The research-specific goals and their metrics are:

- Goal 1: Develop strategies to plan trajectories and maneuvers of single or multiple spacecraft to enable NEA missions, including approach and orbital operations, descent, landing and surface operations, and autonomous guidance, navigation, and control capabilities.
  Metrics: publications in this area, end-to-end robotic asteroid sample return mission design
- Goal 2: Study the impacts of communications and networking constraints within the framework of various protocols on NEA missions, and how such constraints affect and are affected by the trajectories of a constellation of spacecraft at a NEA system.
  Metric: asteroid mission planning tool that incorporates communications constraints
- Goal 3: Improve the gravity field modeling of select NEAs through new observations and the development of numerical modeling algorithms, for the purpose of more effective proximity operation modeling and design for robotic and human NEA mission targets.

Metric: gravity field modeling software using both spherical harmonics and polyhedral body

The New Mexico EPSCoR-specific goals and their metrics are:

- Goal 1: Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while assessing and leveraging the many existing core capabilities relative to NASA in the state.
  Metrics: Evidence of reordered New Mexico and/or institutional priorities; Evidence of how EPSCoR activities have furthered jurisdiction priorities; Financial commitment from the jurisdiction, industry, and participating institutions.
- Goal 2: Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program in space and aerospace related STEM-related research.
  Metric: Number of follow-on grant proposals submitted and/or funded.
- Goal 3: Develop partnerships between NASA research assets and New Mexico academic institutions, federal laboratories, and industry.
  Metric: Extent to which collaborations with New Mexico agencies, industry, research and academic institutions and with NASA have evolved.
- Goal 4: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.
  Metrics: Number of articles submitted to and/or published in refereed journals; Number of talks, presentations or abstracts at professional meetings; Number of patents awarded; Number and gender/ethnicity of students participating in the program research. (We will track students through to degree completion and where they go after graduation.)
- Goal 5: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for STEM education in New Mexico.
  Metric: Increased number and quality of interactions between researchers and NMSGC.

1.9.5 Tracking of Program Progress

The progress and potential towards achieving self-sufficiency beyond the award period of the research capabilities developed under this grant are indicated in the timeline. The assessment metrics will be the primary means for this assessment. An assessment of the stated potential of the proposed research area to continue to grow in importance in the future will require significant input from the space and aerospace industry (including AIAA and IEEE), NASA, AFRL, and others. For our purposes the number of published journal articles, conference presentations, proposals and new research grants in areas related to this project will serve as primary metrics.

1.9.6 Continuity

Through their participation in this research, students are prepared for employment in disciplines needed to achieve NASA's mission and strategic goals. We will encourage participation from New Mexico students enrolled in other NASA sponsored programs, including NMSGC students, and USRP, GSRP, or ESMD programs. Note that two of co-I Butcher's undergraduate students currently supported by NMSGC are likely to stay for graduate education and participate in the proposed effort. Through research participation, internships, and fellowships students become participants in NASA's science and engineering research and acquire sufficient mastery of knowledge for employment with NASA and its contractors. EPSCoR funding provides researchers equipment and material necessary to advance this research area in the state. This funding supports faculty publications, increasing their eligibility for non-EPSCoR funding, and bringing the research team to a level of national competitiveness.

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Patricia C. Hynes, Ph.D.
New Mexico State University
Director, New Mexico Space Grant Consortium
Director, New Mexico NASA EPSCoR
Executive Director, FAA Center of Excellence for Commercial Space Transportation

Education:	B.S.	NMSU	English	1969
	M.S.	NMSU	Higher Education Management	1992
	Ph.D.	NMSU	Business Administration	1998

Appointments:

Executive Director	FAA COE for Commercial Space Transportation	2010-present
Director	New Mexico Space Grant Consortium (NMSGC)	1998-present
Director	New Mexico NASA EPSCoR	2007-present
Executive Director	NMSU Space Development Foundation	2006-present
Co-Chair	Advancing Leaders Program	2005-present
Member	President's Commission on the Status of Women	2004- present
Chair	NSF ADVANCE Research Committee at NMSU	2002- 2004
Member	National Space Biomedical Research Institute Industry Forum	2009

Elected Offices:

Treasurer	National Space Grant Foundation	2006-2010
Treasurer	National Space Grant Alliance – 501C4 Corporation	2002-2004
Treasurer	Southwest Space Task Force	2002-2004
Board Member	National Space Grant Alliance - current Board member	2002-present
Board Member	National Space Grant Executive Committee	2002-2004
Member	National Space Grant Strategic Planning Committee	2002

University Wide Activities:

Founding Director	NMSU Teaching Academy	2001
Officer	NMSU Development Officer	2003-current
Chair	NMSU Leadership Institute	2006-current
Chair	Staff Roles Sub-committee for NMSU President's Roles and Rewards Task Force	2003

Statewide Programs Created and Managed:

Management of New Mexico Space Grant Consortium
Management of New Mexico NASA EPSCoR
International Symposium for Personal and Commercial Spaceflight (ISPCS)
Scholarship and Fellowship Program
Summer Internship Program
America View Program
Research Enhancement Program
Reduced Gravity Student Flight Opportunities Program
Gaining Retention and Achievement for Students Program (GRASP)

BIOGRAPHY of ERIC A. BUTCHER

Department of Mechanical and Aerospace Engineering
New Mexico State University, Las Cruces, NM

Professional Preparation

M.S. *In Progress* (Aerospace Engineering Sciences, focus area: Astrodynamics and Satellite Navigation), expected completion 2012, University of Colorado at Boulder, Advisor: Prof. George Born
* **Ph.D.** (Mechanical Engineering), 1997, Auburn University, Auburn, AL. Advisor: Prof. S. C. Sinha
M.S. (Mechanical Engineering), 1995, Auburn University, Auburn, AL. Advisor: Prof. S. C. Sinha
B.S. (Engineering Physics) with distinction, 1993, University of Oklahoma, Norman
B.M.A., 1991, University of Oklahoma, Norman

Appointments

2007-Present: Dwight and Aubrey Chapman Associate Professor (*tenured*), Mechanical and Aerospace Engineering Dept., New Mexico State University
1998-2006: Assistant & Associate Professor (*tenured*), Mechanical Eng. Dept., University of Alaska Fairbanks
1997-1998: Technical Staff Member, Structural Dynamics Department, Sandia National Labs, Albuquerque, NM

Awards/Honors

2010: Mechanical and Aerospace Engineering Academy Professor of the Year, New Mexico State University
2009: Univ. Research Council Early Career Award for Exceptional Achievements in Creative Scholarly Activity
2007-present: Inaugural holder of Dwight and Aubrey Chapman Endowed Professorship, NMSU
1996-1997: Graduate Research Fellowship, Auburn University

Research Activities

Dr. Butcher is author or co-author on over 47 refereed journal papers and book chapters, 40 conference papers, and has an *h*-index of 9. Research interests have traditionally concentrated in nonlinear dynamics, vibrations, and controls, and have recently expanded into astrodynamics and spacecraft dynamics and controls, particularly in trajectory design, guidance, and navigation issues relevant to libration point and asteroid missions. (*To support these new research efforts, Dr. Butcher has recently been taking on-line graduate courses from the Aerospace Engineering Sciences Department at the University of Colorado, Boulder in topics such as orbital mechanics, orbit determination, spacecraft attitude dynamics and controls, optimal spacecraft guidance, and advanced astrodynamics/celestial mechanics*.) A list of ten recent publications is given below:

1. Argatov, I.I. and E.A. Butcher, "On the Separation of Internal and Boundary Damage in Slender Bars using Longitudinal Vibration Frequencies and Equivalent Linearization of Damaged Bolted Joint Response," *Journal of Sound and Vibration*, in press.
2. Torkamani, S., Butcher, E.A., Todd, M.D., Park, G.P., "Detection of System Changes due to Damage using a Tuned Hyperchaotic Probe," *Smart Materials and Structures*, 20, 025006 (2011).
3. Butcher, E. A., Al-Shudeifat, M. A., "An Efficient Mode-Based Alternative to Principal Orthogonal Modes in the Order Reduction of Structural Dynamic Systems with Grounded Nonlinearities," *Mechanical Systems and Signal Processing*, doi 10.1016/j.ymssp.2010.11.017.
4. Butcher, E.A., and O. A. Bobrenkov, "On the Chebyshev Spectral Continuous Time Approximation for Constant and Periodic Delay Differential Equations," *Comm. Nonlinear Science & Numerical Simulation*, 16, 1541-1554 (2011).
5. Argatov, I.I. and E.A. Butcher, "On the Iwan Models for Lap-Type Bolted Joints," *International Journal of Nonlinear Mechanics*, 46, 347-356 (2011).

6. Al-Shudeifat, M.A. and E.A. Butcher, "New Breathing Functions for the Transverse Breathing Crack of the Cracked Rotor System: Approach for Critical and Subcritical Harmonic Analysis," *Journal of Sound and Vibration*, 330, 526-544 (2010).
7. Al-Shudeifat, M.A. and E.A. Butcher, "Order Reduction of Forced Nonlinear Systems using Updated LELSM Modes with New Ritz Vectors," *Nonlinear Dynamics*, 62, 821-840 (2010).
8. Al-Shudeifat, M.A., E.A. Butcher, and C. Stern, "General Harmonic Balance Solution of a Cracked Rotor-Bearing-Disk System for Harmonic and Sub-harmonic Analysis: Analytical and Experimental Approach," *International Journal of Engineering Science* 48, 921-935 (2010).
9. Sari, M. and E.A. Butcher, "Natural Frequencies and Critical Loads of Beams and Columns with Damaged Boundaries using Chebyshev Polynomials," *Int'l. Journal of Engineering Science* 48, 862-873 (2010).
10. Bobrenkov, O. A., F. A. Khasawneh, E. A. Butcher, and B. P. Mann, "Analysis of Milling Dynamics for Simultaneously Engaged Cutting Teeth," *J. Sound and Vibration*, 329, 585-606 (2010).

Professional Service

- Member of ASME Technical Committee on Multibody Systems and Nonlinear Dynamics (MSND-TC) and chair of Awards Subcommittee
- Associate Editor for *Journal of Computational and Nonlinear Dynamics*
- Reviewer of papers for 13 journals, various conferences
- Reviewer of proposals submitted to NSF, ARO, NMSU Interdisciplinary Research Grants
- Symposium co-organizer for 18th and 19th ASME Biennial Conferences on Mechanical Vibration and Noise (IDETC '01,'03), 9th and 10th International Congress on Sound and Vibration (ICSV'02, '03), 5th, 6th, 7th International Conf. on Multibody Systems, Nonlinear Dynamics, and Control (IDETC '05, '07, '09)
- Search Committee Chair for 2 faculty positions at NMSU in Aerospace Engineering (one of which resulted in the hiring of co-I Sanyal)

Other Relevant Activities

- PI on recently awarded $563,860 DOD grant "Libration Point Orbit Utilization for Tactical Advantage in Communication, Surveillance, and Risk Mitigation"
- PI or co-PI on other aerospace-related grants from AFOSR, NSF, and NASA totaling over $1M
- Recipient of $35K from New Mexico Space Grant for new course development in astronautics-related areas (This funding supported the development of modern up-to-date courses in Orbital Mechanics and Spacecraft Attitude Dynamics and Controls at the undergraduate and graduate levels which are currently being taught by Dr. Butcher and other faculty members.)
- Co-PI on Proposal to NSF in review (with Amit Sanyal): "Robust State and Uncertainty Estimation for Unmanned Systems in the Presence of External Uncertainties"
- NMSU representative on AFRL consortium Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA) directed by Dr. Moriba Jah (NMSU is a new ASTRIA member through recent efforts of Dr. Butcher.)
- Participant, 2008 NASA Minority Serving Institutions Research Partnership, May 12-14, 2008, New Orleans.
- Worked with New Mexico Alliance for Minority Participation (NM-AMP) in conjunction with several research projects to identify students from underrepresented groups with compatible interests for participation on previous research projects

Biography of Amit Sanyal

Professional Preparation

Indian Institute of Technology, Kanpur, India	Aerospace Engineering	B.Tech., 1999
Texas A & M University, College Station, TX	Aerospace Engineering	MS, 2001
University of Michigan, Ann Arbor, MI	Aerospace Engineering	Ph.D., 2004
University of Michigan, Ann Arbor, MI	Mathematics	MS, 2004

Appointments

2004-2006 *Postdoctoral research associate, Arizona State University, Tempe, AZ.*

2007-2010 *Assistant Professor, University of Hawaii at Manoa, Honolulu, HI.*

2010-current *Assistant Professor, New Mexico State University, Las Cruces, NM.*

Honors and Awards

2001 Distinguished Graduate Student Masters Research Award, Texas A & M University.

2002 College of Engineering Fellowship, University of Michigan.

2003 Engineering Academic Scholar Certificate, College of Engineering, University of Michigan.

Relevant Journal Publications

1. A. K. Sanyal, N. Nordkvist and M. Chyba, "An Almost Global Tracking Control Scheme for Maneuverable Autonomous Vehicles and its Numerical Implementation using a Lie Group Variational Integrator," *IEEE Transactions in Automatic Control*, 56(2), pp. 457-462, 2011.
2. A. K. Sanyal, A. Fosbury, N. A. Chaturvedi, and D. S. Bernstein, "Inertia-Free Spacecraft Attitude Tracking with Disturbance Rejection and Almost Global Stabilization," *AIAA Journal of Guidance, Control and Dynamics*, 32, pp. 1167-1178, 2009.
3. A. M. Bloch, I. I. Hussein, M. Leok, and A. K. Sanyal, "Geometric structure-preserving Optimal Control of the Rigid Body," *J. of Dynamical and Control Systems*, 15(3), pp. 307-330, 2009.
4. A. K. Sanyal, T. Lee, M. Leok, and N. H. McClamroch, "Global Optimal Attitude Estimation using Uncertainty Ellipsoids," *Systems and Control Letters*, 57(3), pp. 236-245, 2008.
5. A. M. Bloch, P. E. Crouch, and A. K. Sanyal, "A Variational Problem on Stiefel Manifolds," *Nonlinearity*, 19(10), pp. 2247-2276, 2006.
6. A. K. Sanyal, J. Shen, A. M. Bloch, and N. H. McClamroch, "Stability and Stabilization of Relative Equilibria of Dumbbell Bodies in Central Gravity," *AIAA J. of Guidance, Control and Dynamics*, 28(5), pp. 833-842, 2005.

Professional Service

1. Member of Technical Committees: AIAA Guidance, Navigation and Control Technical Committee, IEEE Technical Committee on Aerospace Control
2. Reviewer: *IEEE Trans. on Automatic Control*, *IEEE Trans. on Control Sys. Tech.*, *SIAM J. on Control and Optimization*, *ASME J. of Dynamic Systems, Measurement, and Control*, *J. of Vibration and Control*, *AIAA J. of Guidance, Control, and Dynamics.*
3. Conference reviewer: *American Control Conference, AIAA Guidance Navigation and Control Conf., IEEE Conf. on Decision and Control, Mathematical Theory of Networks and Systems.*
4. Session chairs: *American Control Conference*, *AIAA Guidance, Navigation and Control Conference.*
5. Member of 2010 AIAA GNC Technical Committee and 2010 IEEE CDC Program Committee.

Biography of Charles Creusere

Professional Preparation

University of California at Davis	Electrical and Computer Engineering	B.S., 1985
University of California at Santa Barbara	Electrical and Computer Engineering	M.S., 1991
University of California at Santa Barbara	Electrical and Computer Engineering	Ph.D., 1993

Appointments

1993-1999 *Research Engineer, Naval Air Warfare Center, China Lake, CA*

2000-2004 *Assistant Professor, New Mexico State University, Las Cruces, NM*

2004-2009 *Associate Professor, New Mexico State University, Las Cruces, NM.*

2009-present *Professor, New Mexico State University, Las Cruces, NM.*

Honors and Awards

1989 Received competitively-awarded graduate fellowship from the Department of Defense

1998 Certificate of Merit for the outstanding technical paper awarded at the AIAA Missile Sciences Conference for the paper "Automatic target recognition directed image compression,"

2008 Awarded the first International Telemetering Foundation Endowed Professorship

2010 Awarded the Frank Carden Chair in Telemetering and Telecommunications

Relevant Journal Publications

1. C.D. Creusere, "A new method of robust image compression based on the embedded zerotree wavelet algorithm," IEEE Trans. on Image Processing, Vol 6, No. 10, Oct. 1997, pp. 1436-1442.
2. C.D. Creusere and A. Van Nevel, "ATR-directed image and video compression," Journal of Aircraft, Vol. 36, No. 4, pp. 626-31, July-August 1999.
3. C.D. Creusere, "Fast embedded compression for video," IEEE Trans. on Image Processing, Vol. 8, No. 12, pp. 1811-16, December 1999.
4. C.D. Creusere, "Motion compensated video compression with reduced complexity encoding for remote transmission," Signal Processing: Image Communications, Vol. 16, pp. 627-42, April 2000.
5. V. Thilak, C.D. Creusere, and D. Voelz, "Passive polarimetric imagery-based material classification robust to illumination source position and viewpoint, IEEE Transaction on Image Processing, January 2011.
6. Castorena, J.; Creusere, C.D.; Voelz, D.; , "Modeling lidar scene sparsity using compressive sensing," Geoscience and Remote Sensing Symposium (IGARSS), 2010 IEEE International , vol., no., pp.2186-2189, 25-30 July 2010.

Professional Service

1. Member of Technical Committees: IEEE Data Compression Conference, IEEE International Conference on Acoustics, Speech, and Signal Processing, IEEE International Conference on Image Processing
2. Associate Editor: *IEEE Trans. on Image Processing*, *IEEE Trans. on Multimedia*
3. co-Technical Program Chair: *IEEE Southwest Symposium and Image Analysis and Interpretation*, 2012

Daniel J. Scheeres, PhD.
A. Richard Seebass Endowed Chair Professor
Colorado Center for Astrodynamics Research
Department of Aerospace Engineering Sciences
The University of Colorado at Boulder

ADDRESS

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Boulder, Colorado 80309-0429	(720) 544-1260 (voice)
scheeres@colorado.edu	(303) 492-7881 (fax)

EDUCATION

Ph.D. Aerospace Engineering The University of Michigan, 1992

M.S.E. Aerospace Engineering The University of Michigan, 1988

B.S.E. Aerospace Engineering (*summa cum laude*) The University of Michigan, 1987

B.S. Letters and Engineering Calvin College, 1987

ACADEMIC & INDUSTRY EXPERIENCE

The University of Colorado at Boulder
Department of Aerospace Engineering Sciences
1/08 – present A. Richard Seebass Endowed Chair Professor

The University of Michigan
Department of Aerospace Engineering
9/99 – 12/07 Assistant/Associate Professor

Iowa State University
Department of Aerospace Engineering and Engineering Mechanics
8/97 – 8/99 Assistant Professor

Jet Propulsion Laboratory, California Institute of Technology
Navigation and Flight Mechanics Section
9/92 – 7/97 Senior Member of Engineering Staff

RESEARCH ACTIVITIES

Author or co-author on over 150 peer-reviewed journal papers, notes and book chapters and over 270 conference papers and abstracts. Primary advisor to over 18 PhD. students now working in academia, government labs and industry. Research focused at the intersection of science, mathematics and engineering, Scheeres has an active research program that spans space science, dynamical astronomy, astrodynamics and celestial mechanics.

Asteroid and Comet Science Member of the Astrodynamics Science Team on the Japanese Hayabusa mission. Participating scientist on the Near Earth Asteroid Rendezvous (NEAR) Radiometric Science team. NASA funded investigations into the basic mechanics and dynamics of the asteroid and comet environment. Radiometric Science Co-I on the OSIRIS Rex New Frontiers proposal. PI on the BASiX Discovery Mission proposal.

Astrodynamics and Celestial Mechanics Orbital dynamics of highly perturbed systems using analytical, semi-analytical, and numerical methods. Hamiltonian dynamical systems. Optimal control of spacecraft and mechanical systems in challenging environments. Orbit determination and covariance analysis of spacecraft. Navigation and control of space trajectories.

Space Situational Awareness Orbit determination and correlation for short-arc observations. Space object characterization using optimal control and estimation theory.

VITA – DANIEL A. KLINGLEMSITH III

Magdalena Ridge Observatory
New Mexico TECH
Socorro, NM 87801
Phone: 505-835-6802
email: dklinglesmith@mro.nmt.edu

EDUCATION:

BS	St. Louis University, Physics	1961
MS	Indiana University, Astronomy	1964
Ph.D.	Indiana University, Astrophysics	1967

Recent efforts: Klinglesmith is an experienced observer and computer software expert. He is responsible for the automation of the Etscorn Campus Observatory, Celestron C-14 Telescopes and CCD cameras. He has also taught an introductory astronomy laboratory using the Etscorn Campus Observatory CCD camera and high resolution spectrograph during the 1999-2002 School years. He is well versed in the techniques of data reduction and image analysis. He is responsible for directing students doing asteroid light curve research.

EXPERIENCE:

Magdalena Ridge Observatory site characterization Lead	2002 - current
New Mexico TECH, Lecturer in Physics	1999 - 2002
NASA Goddard Space Flight Center	1966 - 1996
Co-Director of the Joint Observatory for Cometary Research, New Mexico Institute of Mining and Technology	1987 - 1990
Co-Investigator for the Large Scale Phenomenon Network of the International Halley Watch	1983 - 1990

OTHER RELATED VOLUNTEER ACTIVITIES:

Education and Outreach program director for Magdalena Ridge Obsevatory	2002 - 2011
"Project Astro" Astronomer with Sarracino Middle School, Socorro, New Mexico	1997 - 2003
Asteroid Search & Position measurements, Etscorn Campus Observatory	1999 - 2003
Asteroid Light curve measurements, Etscorn Campus Observatory	2003 - 2004

SELECTED PUBLICATIONS:

Q. Jamieson & D.A. Klinglesmith III, 2004, *Period determination of asteroids 1508 Kemi and 5036 Tutle*, Minor Planet Bulletin 31, 88-89.

D.A. Klinglesmith III, R. Alvarado, M.J. Creech-Eakman, B. O'Donovan, B. Seneta, J.S. Young, 2004, *Astronomical site monitoring for the Magdalena Ridge Observatory,* Proceeding of SPIE 5491-146, in press

B.O'Donovan, B. Seneta, A. Bharmal, J.S. Young, D.A. Klinglemsith, 2004, *DIMMWIT measurements of Fried's parameter r0 and the speckle lifetime to at Coast*, SPIE 5491-147, in press

E.J Grayzeck, M.F. A'Hearn & D.A. Klinglesmith, III 1997, *Addition of Spacecraft Data to the IHW Comet Halley CD-ROM Archive*, PS&S, 45, 345.

F.L. Roesler, D.A. Klinglesmith, III; F. Scherb, E.J. Mierkiewicz, E. J. & R.J. Oliversen 1997, *Fabry-Perot Observations of Comet Hale-Bopp* H_2O^+ *Velocity Fields,* DPS, 29, 37.23.

S. Hoban, N.H. Samarasinha, M.F. A'Hearn & D A. Klinglesmith, 1988, *An Investigation into the Periodicities in the Morphology of CN Jets in Comet P/Halley,* A&A, 195, 331.

N.H. Samarasinha, M.F. A'Hearn, S. Hoban, & D.A. Klinglesmith, 1986, *CN Jets of Comet P/Halley-Rotational Properties*, ESA SP-250, a'l, p487

Dr. Moriba Kemessia Jah
Air Force Research Laboratory
3550 Aberdeen Ave. SE
Kirtland AFB, NM 87117
Phone: 505-853-2629
Fax: 505-846-7877

Professional Preparation

Ph.D. 2005, University of Colorado, Boulder, Aerospace Eng. Sciences, Advisor: Prof. George Born
M.S. 2001, University of Colorado, Boulder, Aerospace Eng. Sciences, Advisor: Prof. George Born
B.S. 1999, Embry-Riddle Aeronautical University, Aerospace Engineering

Work Experience

2007 – Present : Air Force Research Laboratory, Kirtland AFB, NM
Technical Advisor, Guidance Navigation and Control Group (AFRL/RVSVC)
Director, Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA)
2006 – 2007: Oceanit Laboratories, Inc., Kihei, HI Senior Scientist
1999 – 2006: NASA/Jet Propulsion Laboratory, Pasadena, CA
Navigation Engineer/Orbit Determination Analyst
1997 – 1999: Microcosm Inc., Torrance, CA Space Mission Design and Orbit Analyst
1996 – 1999: Embry-Riddle Aeronautical University, Prescott, AZ
NASA Space Grant Researcher
1996 – 1997: Los Alamos National Lab, Los Alamos, NM Space Engineering Assistant

Relevant Activities, Organizations, Awards, Honors, and Offices Held

- Adviser, *National Research Council*
- Associate Editor, Space Systems Area, IEEE Transactions on Aerospace and Electronic Systems
- Member of Space Flight Mechanics Technical Committee for the *American Astronautical Society*
- Chair of AAS Space Surveillance Technical Committee
- Senior Member *American Institute of Aeronautics and Astronautics* (AIAA)
- Member *IEEE Aerospace and Electronic Systems Society (*AESS*)*
- Member *International Society for Information Fusion* (ISIF)
- Member *Sigma Gamma Tau* National Aerospace Engineering Honorary
- Reviewer, *Journal of Guidance, Control, and Dynamics* and *Acta Astronautica*
- 2009 *NASA Group Achievement Award* for the Nanosail-D mission support
- 2007 *NASA Space Act Award*
- 2005 *NASA Group Achievement Award* for navigation of the Mars Reconnaissance Orbiter
- 2001 *NASA Group Achievement Award* and *Aviation Week & Space Technology Laurel Award* for navigation of the Mars Odyssey spacecraft
- Supported spacecraft navigation operations for the Japanese Space Agency (JAXA) on the Hayabusa (Muses-C) mission to asteroid Itokawa
- Provided navigation operations support for European Space Agency (ESA) on Mars Express
- Co-developer of next generation modular astrodynamics software tool suite GMAT
- Developer of 6-Degree-of-Freedom Unscented Kalman Filter software for processing inertial sensor data for estimation of spacecraft states and modeling parameters
- Designer of Mars Reconnaissance Orbiter in-flight attitude control system thruster calibration

Research Activities

Research interests target spacecraft orbital and attitude dynamics and estimation, navigation, optimal control and trajectory optimization, state estimation/filtering, and information fusion. Dr. Jah has over 33 journal and conference papers and seven invited lectures/papers.

Dr. Thomas Alan Lovell

Education Ph.D./Aerospace Engineering 2001 Auburn University Auburn, AL

Awards Received

- AIAA Space Systems Award Winner, 2007 (XSS-11 Mission Team)
- Air Force Research Laboratory Dr. Harold Gardiner Director's Cup Winner, 2007 (TacSat-2 Mission Team)
- Air Force Research Laboratory Commander's Cup Winner, 2006 (XSS-11 Mission Team)
- U.S. Air Force Agile Acquisition Transformation Leadership Award, 2005 (XSS-11 Mission Team)

Research Interests

- Spacecraft orbital and attitude dynamics, optimal control and trajectory optimization, state estimation/filtering, multivariable robust control, and use of intelligent systems (neural networks and genetic algorithms) for system modeling and prediction.

Current Position

Research Aerospace Engineer, 2001-present, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM

- Member of Astrodynamics/Guidance, Navigation, & Control Team; duties include spacecraft mission planning, orbit/trajectory design, R&D support and contract management related to these areas
- Director of the Space Vehicles Directorate's Space Scholars Summer Intern Program

Honoraries/ Professional Societies

- Phi Kappa Phi
- Sigma Gamma Tau Aerospace Honorary
- Tau Beta Pi Engineering Honorary
- AIAA (Senior Member), 1994-present, Member of AIAA Astrodynamics Technical Committee, 2002-present
- American Astronautical Society (Senior Member), 2001-present, Member of AAS Spaceflight Mechanics Technical Committee, 2003-2009
- American Helicopter Society, 1990

Other Professional and Academic Experience

- Member of approximately 20 graduate students' thesis/dissertation committees
- Member of Organizing Committee for 3rd & 4th International Symposium on Formation Flying, Missions & Technologies
- Contributed to the 3rd edition of the book *Fundamentals of Astrodynamics* by David Vallado, 2007 (cited on p. 351)
- Overall Technical Chair for AAS/AIAA Astrodynamics Specialist Conference, 2006, 2009
- Session Chair for AAS/AIAA Spaceflight Mechanics Meeting, 2003-present
- Session Chair for AAS/AIAA Astrodynamics Specialist Conference, 2003- present
- Regular reviewer of manuscripts for *AIAA Journal of Spacecraft and Rockets*, *AIAA Journal of Guidance, Control, and Dynamics, Celestial Mechanics and Dynamical Astronomy*, *Advances in Space Research*, and *AAS Journal of the Astronautical Sciences*

Conference Papers and Journal Articles

- Authored/co-authored 39 conference papers and 11 journal articles (list available upon request) through a master's degree and into a Ph.D. program. In addition to financial support, participating students have access to professional development workshops, a graduate seminar, editorial assistance with thesis preparation, networking with faculty, and assistance in identifying additional fellowships and grant opportunities. During the first two years of graduate study at NMSU, strong focus is placed on increasing students' knowledge and commitment of the opportunities available to Ph.D. recipients in their respective fields, thereby facilitating their progress toward attainment of the Ph.D. Both the URA and BD programs have facilitated underrepresented students to make the critical transition to graduate education.

I support the PIs' plans to involve underrepresented students at both the undergraduate and graduate levels. If NASA funds the proposed research, the New Mexico AMP staff will be able to assist the PIs and their students to increase the visibility and impact of their research in the state of New Mexico. We are excited about our collaboration, and we expect to actively participate to ensure the success of the proposed project.

Sincerely,

Ricardo B. Jacquez
Dean of Engineering and Regents Professor
Director, New Mexico AMP

February 9, 2011

Patricia Hynes
Director, New Mexico Space Grant Consortium and New Mexico NASA EPSCoR
New Mexico State University
P.O. Box 30001, MSC SG
Las Cruces, NM 88003

Dear Dr. Hynes,

New Mexico Tech's contribution to the NASA EPSCoR proposal, "Proximity Operations for Near Earth Asteroid Exploration" will consist of observations of NEO light curves for the purpose of modeling the shape of NEOs. The selected NEOs will be observed at numerous phase angles during the course of the project. These observations and data reduction will be undertaken by undergraduate students from New Mexico Tech under the direction of Dr. Daniel A. Klinglesmith III at the Etscorn Campus Observatory.

The Observatory is equipped with 2 Celestron C-14 telescopes with SIBG CCD camera systems. One of these C-14s will be available continuously for the duration of the project. The second one will be available when not being used by astronomy lab students.

We will hire 3 students to make the observations under the direction of Dr. Klinglesmith. With 3 students we will be able to work around class workloads and provide continuous coverage of the objects.

Dr. Klinglesmith has developed software that will allow the display of the developing light curve in near real time. This will allow for continuous monitoring of the quality of raw data. Also he has software that will combine multiple nights worth of data to determine the shape and period of the asteroid light curve. This data will then be passed onto the people responsible for modeling the shape of the asteroid.

Sincerely,

Dr. Daniel A. Klinglesmith III
Magdalena Ridge Observatory
New Mexico Tech
Socorro, NM 87801

DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY (AFMC)

February 16, 2011

Dr. Patricia Hynes
Director of New Mexico NASA EPSCoR and New Mexico Space Grant Consortium

Dr. Hynes,

This letter is to express support for the proposal, *Proximity Operations for Near Earth Asteroid Exploration*, to the NASA/EPSCoR program. Although asteroid exploration is not directly relevant to AFRL's research mission, the subject of proximity operations in the proposed work has potential application to AFRL's Space Situational Awareness (SSA) and Operationally Responsive Space (ORS) programs, which are major areas of concern in the Space Vehicles Directorate at Kirtland AFB, New Mexico.

It is noteworthy that New Mexico State University (through the efforts of Drs. Eric Butcher and Amit Sanyal) is a recent addition to AFRL's Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA), a multi-university consortium providing expertise and state-of-the-art knowledge in astrodynamics-related areas of interest to the Air Force. Both Dr. Butcher and Dr. Sanyal collaborate with certain members of the AFRL staff, and both of them have expressed a desire to work with AFRL staff at Kirtland AFB during the summer as Summer Faculty Fellows.

The original strategies that are outlined in this proposal for approach and orbital operations, descent and surface operations, communications, guidance, navigation, and control, and asteroid modeling and observation are at the cutting edge of current research in these areas in the spaceflight community. The participation of Dr. Daniel Scheeres from CU Boulder, who has much research experience in these areas, will also help to ensure the success of this project if funded. In addition, the students who work on this project may participate in the Space Scholars Program at AFRL to gain further experience and training.

As collaborators, our contribution to the project will include providing technical knowledge in the areas of astrodynamics, spacecraft guidance, navigation, and control, relative motion, and orbit determination. Due to the fact that linear covariance may not be valid in such extreme orbital environments as around asteroids, the use of other methods of approximation of the true error probability distribution of states and model parameters which have been applied recently at AFRL is another technical area in which our knowledge may assist you in this project.

If you need any further details from me in support of this proposal, please let me know.

Sincerely,

Thomas Alan Lovell, Ph.D.
AFRL/RVSV
Research Aerospace Engineer
ASTRIA Project Coordinator
Space Scholars Program Director