NEW MEXICO EPSCOR

PROXIMITY OPERATIONS FOR

NEAR EARTH ASTEROID EXPLORATION

Grant number: NNX11AQ35A

PI: Patricia Hynes

New Mexico State University

MSC SG, Box 30001

Las Cruces, NM 88003

Science PI: Eric A. Butcher

New Mexico State University

MSC 3450, Box 30001

Las Cruces, NM 88003

Sep. 1, 2011-Aug. 30, 2014

Progress Report: Year 2

July 2, 2013

Proximity Operations for Near Earth Asteroid Exploration

New Mexico EPSCoR

Progress Report: Year 2

Research Accomplishments Measured Against the Proposed Goals and Objectives:

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.
Progress on Goal #1: Research on autonomous approach, descent, and hovering strategies for a spacecraft at an asteroid is well underway. Control strategies for both uniformly rotating asteroids and tumbling asteroids are being designed. Two conference papers being submitted to the 2013 Astrodynamics Specialist Conference focus on body-fixed hovering control over a uniformly rotating asteroid using geometric mechanics, and observer-based hovering control over a tumbling asteroid. For the second case, the state and gravity field (second degree and order) of asteroid Toutatis is estimated using range-only measurements from selected points on the asteroid's surface. These "ground stations", which are assumed to be located on the surface in advance, are simple transmitters that enable the spacecraft to measure one-way light time and thus the range data which is processed to yield the estimated state and gravity field. Fig. 1 shows a spacecraft trajectory for observer-based descent and hovering control about Toutatis in the asteroid-fixed frame to a specified point on the asteroid's minor axis. In addition, research is in progress on an integrated framework for GN&C of a spacecraft during autonomous rendezvous and proximity operations near a tumbling target. Finally, work is underway to extend the analysis of the nonlinear orbital dynamics around uniformly rotating triaxial ellipsoidal bodies to the case of tumbling asteroids, including finding relative equilibria, invariant manifolds, and periodic orbits. A paper on this work will be submitted to the 2014 AAS Spaceflight Mechanics Conference.

In terms of orbital mechanics, the asteroid/spacecraft scenario being modeled here is referred to as a Restricted-Full Two-Body Problem (meaning one body is insignificant in both mass and shape relative to the other), and a key point is that it takes into account the effect of a large body's shape and spin rate on system dynamics. This is critical because many asteroids spin at high rates and they often have highly irregular shapes. The use of a triaxial (sometimes referred to as "scalene") ellipsoid keeps the geometry of the system simple. A full derivation of the system's equations of motion has been done by co-PI Scheeres in prior work. To perform the numerical integration required to implement computer simulations based on these equations of motion, we use a 4th & 5th order paired Runge-Kutte integrator which we have found to be as accurate in this application as a 7th & 8th order integrator but with reduced computational complexity.

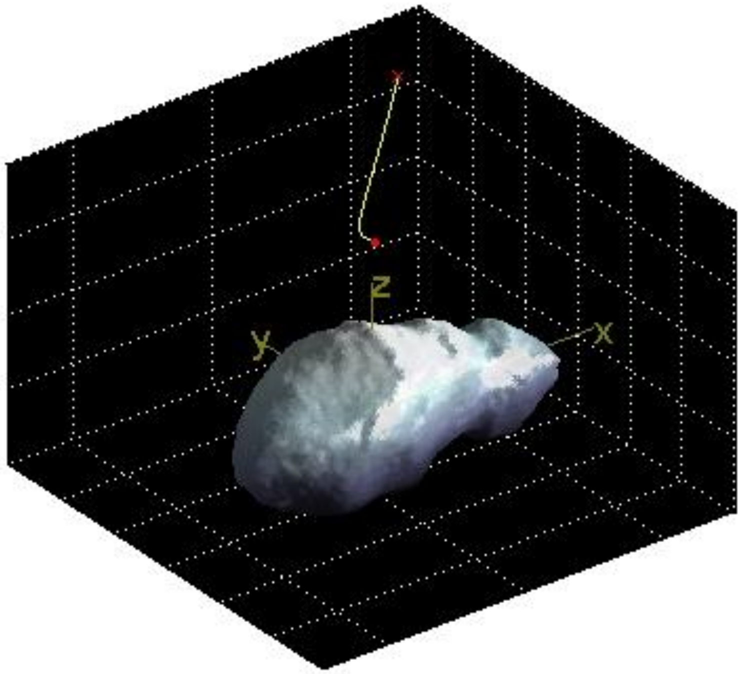

Figure 1: Spacecraft trajectory for observer-based hovering control about the tumbling asteroid Toutatis in the asteroid-fixed frame. The controller effectively causes the spacecraft to descend to and hover over a specified point on the asteroid's minor axis.

Research by co-I Scheeres' group has been continued on developing methods and analyses to support close proximity operations about asteroids. In the initial year of support, a variety of approaches were considered and begun. At least two of these were transitioned to funded proposals from the NASA NSTRF program.

1. Efficient ways to automatically map out the forward sets of a spacecraft given a certain level of control authority. By developing such maps an autonomous mission planner can make informed decisions on what courses of control action will yield the best outcome, see Fig. 2. Past supported student David Surovik, currently funded by an NSTRF grant.
2. Stability of spacecraft motion in relatively distant orbits about small asteroids and comets. Coupled effects of asteroid gravitational attraction and solar gravity and radiation pressure perturbations can cause both stable and unstable motions to exist. Deeper understanding of these dynamics is lacking, and has been a focus of research. Currently funded student Samantha Rieger, newly awarded an NSTRF grant to pursue this work.
3. Ballistic deployment of science packages to the surfaces of asteroids has been studied. This is a refinement of a previously developed concept for asteroid exploration, see Fig. 3. Currently funded student Simon Tardivel is currently supported for this work.

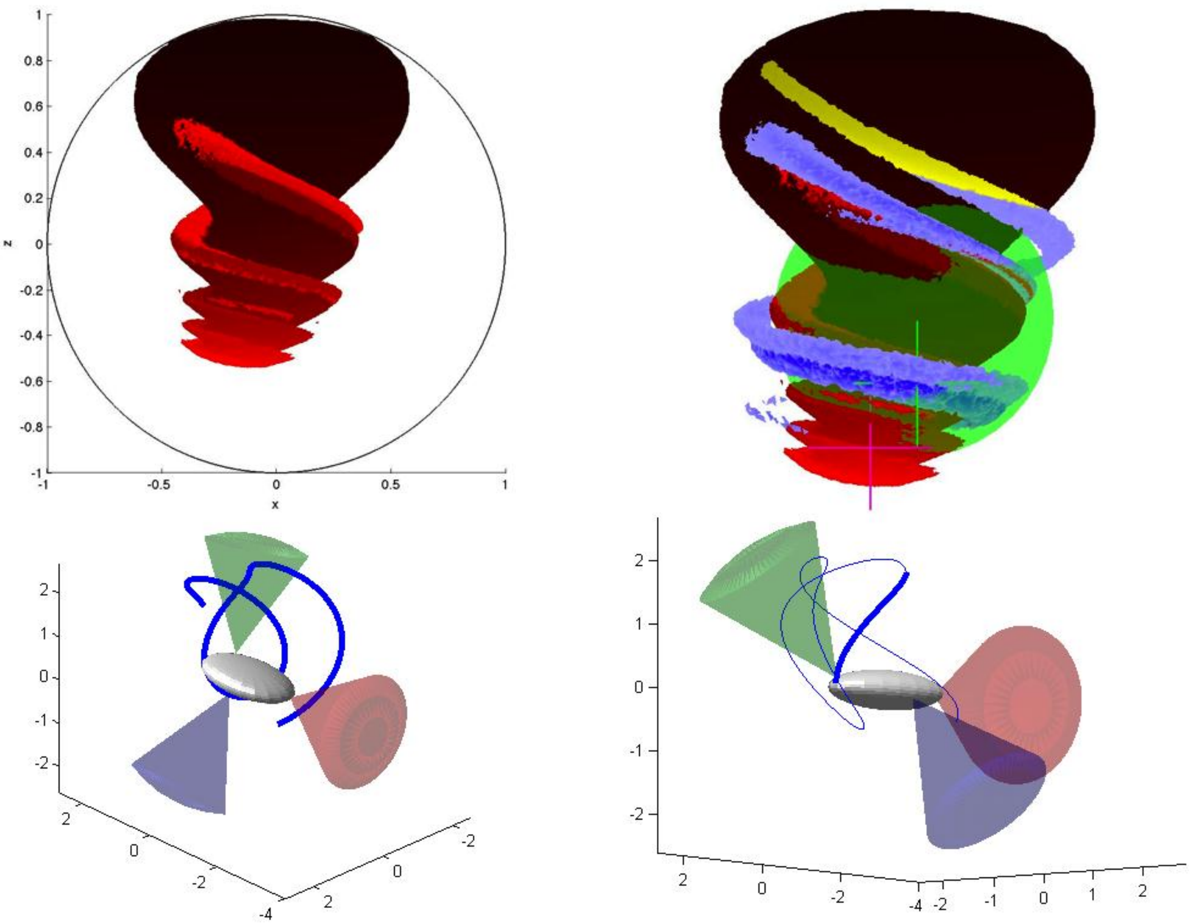

Figure 2: Top: Control sets for a close proximity trajectory in the vicinity of a small body. Red - Impact trajectories, Yellow - Escape trajectories, Blue - Non-escape/impact trajectories that satisfy observation goals. Bottom: Example trajectories from the control set. Cones are desired observation regions on the surface.

Research on autonomous approach and GN&C strategies for spacecraft rendezvous with a tumbling target, started during the first year, has lead to some publications with advanced feedback control techniques that can be applied to tumbling asteroids. The main focus of the second year (2012-2013) of this project has been to estimate the relative motion of an asteroid from remote measurements from a spacecraft in its proximity, using methods derived from geometric mechanics. These methods include both discrete-time filtering techniques, as well as continuous-time observer schemes for estimation of relative motion of one rigid body with respect to another, when both bodies (spacecraft and asteroid) could be tumbling. Results from a continuous-time observer, showing convergence of estimate errors for relative pose of a spacecraft with respect to an asteroid, is given in Figure 4. Until now, the asteroid has been assumed to be spherical with a simple central gravity model.

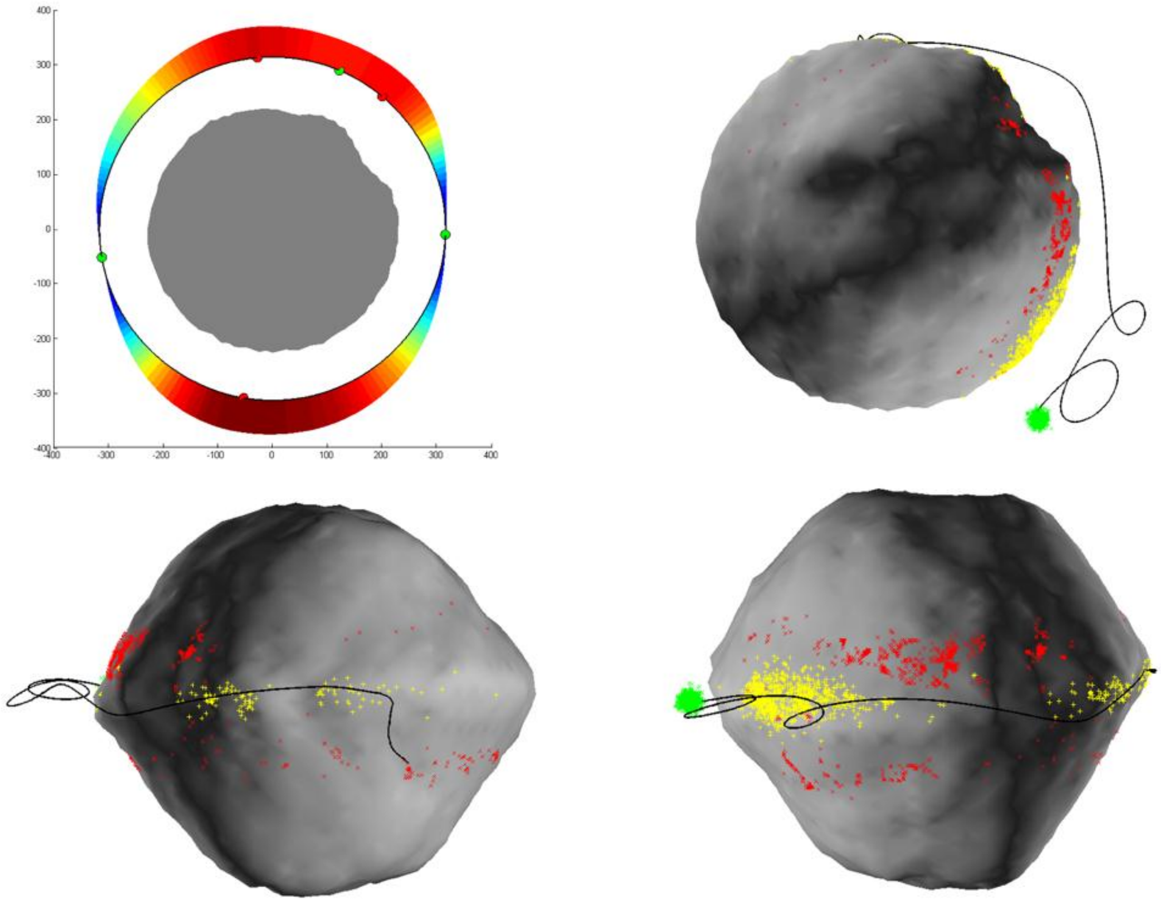

Figure 3: Top-left: Zero-velocity curves about asteroid 2008 EV5, delineating where synchronous orbits lie. The other figures show a series of deployment trajectories to the surface of the asteroid. Green is first deployment position, yellow is first bounce on the surface, red is the final location of the probes on the surface.

The next phase of work would be to consider a non-spherical asteroid with a more realistic gravity model given by a spherical harmonic expansion (see related work on Goal #3). Recent work on autonomous GN&C of a formation of three spacecraft with collision avoidance has also been accepted in a conference in the third week of June 2013. Such formations could be used as a sensor network for gathering data in the proximity of a NEA.

<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>Progress on Goal #2:</u> We continue to move forward on the first task associated with this project Goal which is described as follows in the proposal: *Begin communications and telemetry studies, and integrate communications constraints into orbital and proximity operations.* Specifically, starting with asteroid orbital simulation models originally designed by project co-PI Scheeres and implemented in Matlab by student Thomas Critz working under the direction of co-I Butcher

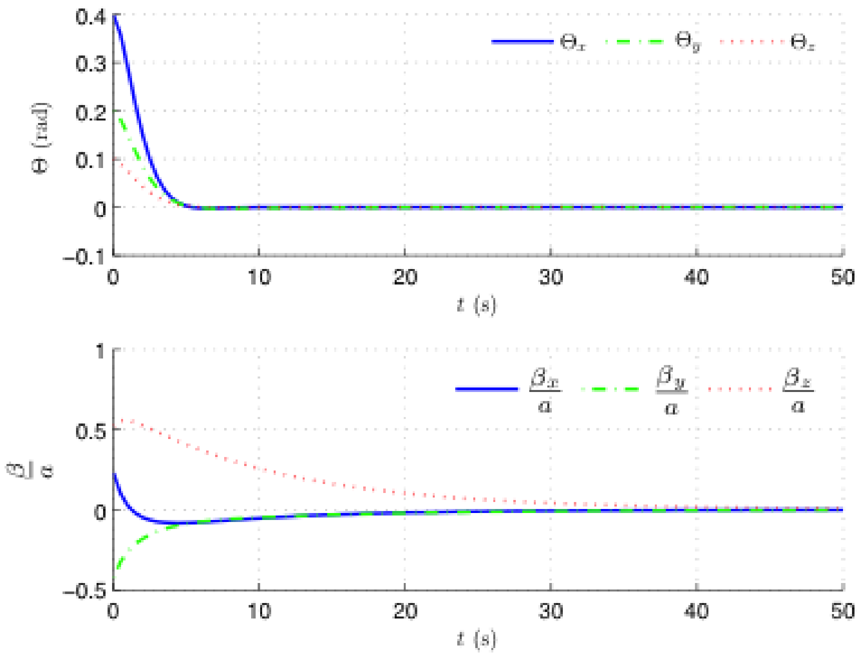

Figure 4. Estimate errors for relative pose of a spacecraft with respect to a spherical asteroid, given in exponential coordinates.

we have continued to analyze and quantify the communication tradeoffs associated with operating in the vicinity of various near-earth asteroids. Our focus this year has been to study the data rates and required data buffer sizes for communications between a single orbiting spacecraft and remote sensor platforms placed at various locations on the surface of the asteroid. The assumption here is that the spacecraft is required to act is a relay for data being collected by the surface platforms so that this data can either be shared amongst the platforms for local collaborative processing or transmitted back to earth. This thrust illustrates what one might call the 'best case' communications scenario: if an unobstructed line of sight exists between a surface platform and the spacecraft, we assume that reliable communication is possible at some fixed bit rate. In a real system, line of sight is necessary for reliable communication (at all radio frequencies that are practical for space communications, at least), but it is not sufficient to guarantee error-free reception. In general, one must also consider the signal to noise ratio (SNR) of the system. Calculating the SNR requires information about the antennas and modulation hardware as well as RF background noise models (which depends not only on the antenna selection but also on the positions of the surface and space platforms). We have actually incorporated such models into our current simulator, but we have not yet performed extensive case studies or Monte Carlo analysis with the resulting system.

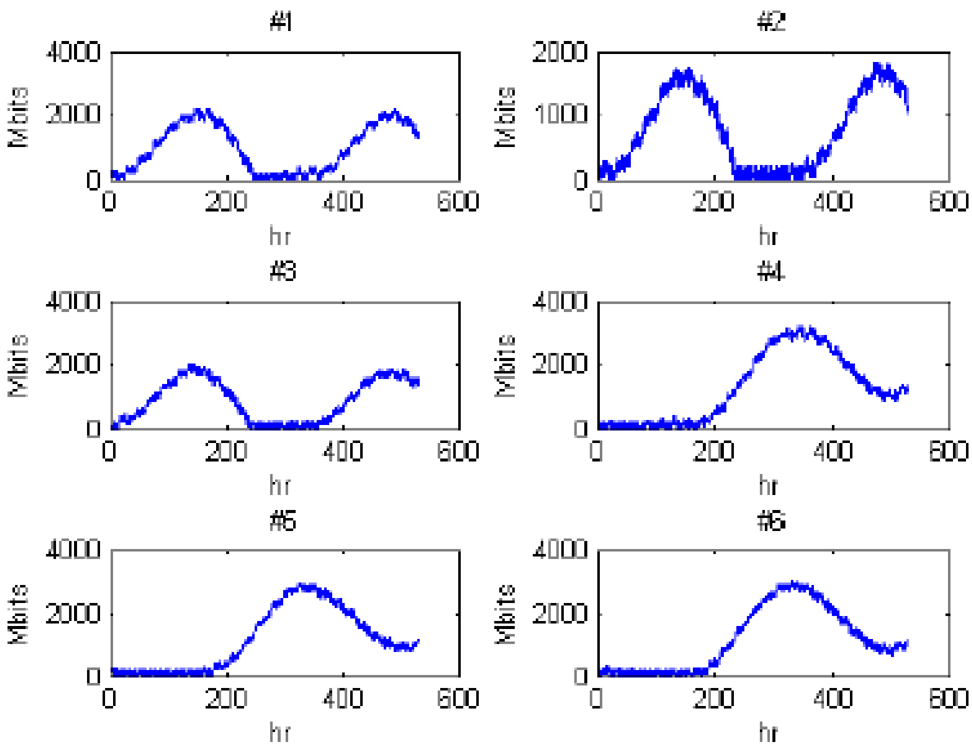

Figure 5: Buffer fullness over time for Vesta Orbit #1.

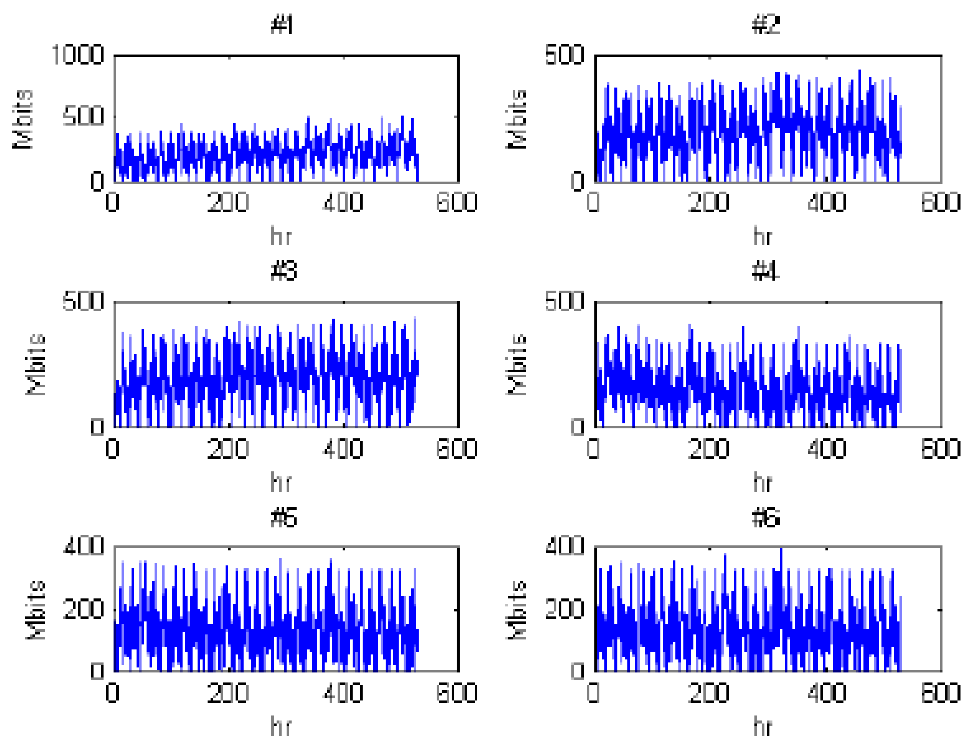

Figure 6: Buffer fullness over time for Vesta Orbit #2.

The results from our current analyses will be presented at the International Telemetering Conference in October 2013 and published in the proceedings. Consider, for example, Figures 5 and 6 which contrast the data buffer fullness for 6 uniformly distributed surface probes collecting data at a rate of 20 kbits/second with the spacecraft being in two different orbits around the asteroid Vesta. Comparing these figures, we see that the required buffer size (as given by the maximum plotted value over a period) is almost 4 times higher for the first orbit than it is for the second. This tradeoff has obvious application in system design as well as in mission planning. Furthermore, if we are interested in communicating information between surface probes using the spacecraft as a relay (for performing distributed data processing), Tables 1 and 2 show that the orbit selected (for Vesta, again) has a tremendous effect on system throughput with the relative information rates differing by almost 50%.

Table 1. Effective data transfer rate in kbits/sec for Vesta Orbit #1.

1	0	13.567	13.5121	13.3906	13.4416	13.4141
2	13.6062	0	14.2726	13.7787	14.2217	14.2373
3	13.5788	14.3824	0	13.7434	14.2569	14.1903
4	13.5435	13.8571	13.8257	0	15.2056	15.2056
5	13.6689	14.4608	14.4137	15.2761	0	16.0013
6	13.6807	14.4451	14.3549	15.2957	16.0444	0

Table 2. Effective data transfer rate in kbits/sec for Vesta Orbit #2.

1	0	23.1553	23.1631	23.1004	23.3356	23.171
2	23.2337	0	24.4097	24.5429	24.6253	24.5351
3	23.2102	24.5939	0	24.5508	24.6841	24.4998
4	23.0063	24.4724	24.4606	0	33.159	33.1316
5	23.2337	24.5743	24.6331	33.163	0	33.6686
6	23.265	24.6057	24.4959	33.0806	33.8019	0

Relating to both Goals 2 and 3, we have also started another thrust during the current year. The idea of this new thrust is to use the communications signals going between the surface probes and the orbiting spacecraft to also do ranging in a manner similar to GPS. The idea would be to use the earth-acquired spacecraft position to determine the absolute positions of the surface probes and then use those positions (along with the orbital model) to refine the spacecraft position. In this manner, we hope to be able to better extract information that can be used to improve the gravitational model for the asteroid in question. While we do not yet have results to support this concept of operation, we believe that it has a great deal of potential merit and thus will focus much of our efforts on it in the coming year.

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.
Progress on Goal #3: During the second year of this grant Klinglesmith and his students continued to observe and publish asteroid light curves. He has 5 undergraduate students working with him. Three are funded under this grant and the other two from other sources within New Mexico Tech. Between June 2012 and June 2013 17 papers with lightcurves for 38 individual asteroids have been published or submitted for publication in Minor Planet Bulletin which is refereed journal. One paper (Warner, Klinglesmith, Skiff, 2012) on the shape model for 47035 (1998 WS) published and we have made a physical model using a 3-D printer, see Figure 7. Of the published and submitted papers in the Minor Planet Bulletin each student has one paper as the sole author.

Figure 7: Physical shape model of asteroid 47035 (1995 WS). The asteroid has an actual largest dimension estimated to be 9 km.

The continuous-time observer that has been obtained as a result of research on Goal #1, has been used to additionally estimate the gravity parameter of a spherical asteroid. This work has been recently accepted as a conference paper, and a numerical simulation result from this paper is given in Figure 8. Future work will concentrate on estimating gravity parameters of a spherical harmonic model of the gravity of a non-spherical asteroid.

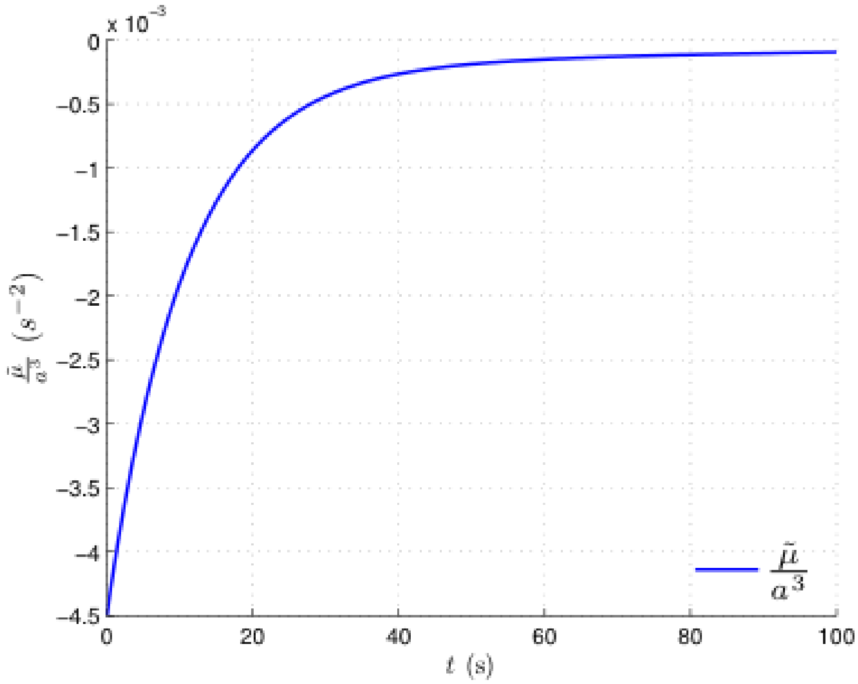

Figure 8. Time evolution of estimation error for the gravity parameter of a spherical asteroid obtained from remote measurements of an orbiting spacecraft.

Also, during the second year of the project the New Mexico co-Is have participated in several Skype conferences with co-I Scheeres at University of Colorado, wherein Prof. Scheeres made presentations on his past asteroid-related research and answered many questions from the other co-Is and students. These presentations have mostly focused on the gravity modeling and orbital aspects of the asteroid environments for many different classes of asteroids, as well as on his past experiences participating in the NEAR and Hayabusa missions.

Goal 4: 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.
Progress on Goal #4: PI Butcher continues to develop a state-of-the-art orbital mechanics 3D visualization laboratory which is funded by his recent grant from AFOSR. This laboratory will be used for the current project as well as serving as an outreach tool for visiting K-12 students at New Mexico State University.

Goal 5: Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program in space and aerospace related STEM-related research.
Progress on Goal #5: The team has a number of publications published, in press and in review (see list below for details). These publications will support the team for follow-up research

funding, in particular, for development of a credible IGERT proposal. During the first year Sanyal and Butcher submitted a proposal that was funded by the National Science Foundation ($278,158) for a three-year project "Robust State and Uncertainty Estimation for Unmanned Systems in the Presence of External Uncertainties." During the second year co-I Creusere was funded for the submitted proposal *Pulse complexity based LIDAR scene modeling for sparse reconstruction and super-resolution* by the National Geospatial Intelligence Agency ($150,000}, while co-I Sanyal submitted the proposal "Stable Control of Small Spacecraft using Geometric Mechanics" to the NASA Small Spacecraft Technology Program in collaboration with NASA Ames Research Center. Co-I Scheeres submitted two proposals to NASA's NSTRF program, which he was recently awarded. This is for work in autonomous mission planning and will fund his students David Surovik and Simon Tardivel, who were initially funded on this project. Due to this, a different CU Ph.D. student, Samantha Rieger, will be brought into the current project while Surovik's and Tardivel's work will still be tied to the basic project goals.

<u>Goal 6</u>: Develop partnerships between NASA research assets and New Mexico academic institutions, federal laboratories, and industry.
<u>Progress on Goal #6:</u> During the second year of the project collaborations have been strengthened at AFRL in Albuquerque, NM. In particular, co-I Sanyal spent summer 2012 at AFRL as an ASEE-funded summer faculty fellow working with our AFRL collaborators (Lovell and Jah). In addition, both Butcher and Sanyal have made presentations during the past year at AFRL and to AFRL staff that have visited NMSU. Butcher is making a trip to AFRL this summer to give a presentation and meet with Jah and Lovell, as well as other AFRL staff. Sanyal is currently working with AFRL staff Fred Leve and Scott Erwin as well, and also recently traveled to NASA Ames laboratory to establish partnerships for the purpose of proposal development.

<u>Goal 7</u>: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.
<u>Progress on Goal #7:</u> The graduate (M.S. and Ph.D.) programs in aerospace engineering at NMSU (the only aerospace program in the jurisdiction) recently graduated its first M.S. students, including two students of co-I Sanyal in Fall 2012 and one of co-I Butcher in Spring 2013. Currently Butcher and Sanyal jointly have four Ph.D. Aerospace Engineering students, which is one less than the total number in the department, and one of these (Butcher's student) is due to graduate in Fall 2013 as the first aerospace Ph.D. graduate in the program. Three years ago when the graduate AE program was just beginning, three graduate courses in astronautics were added to the curriculum: AE 562 Astrodynamics was taught for the first time in Fall 2011 by Butcher, AE 561 Spacecraft Attitude Dynamics and Controls was taught in Spring 2012 by Sanyal, and AE 565 Statistical Orbit Determination was taught for the first time in Fall 2012 by Butcher. This coming fall 2013 Butcher will teach AE 562 once more. These courses are helping developing a solid graduate program in astronautics at NMSU which will help to train students involved in the current project.

<u>Goal 8</u>: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for STEM education in New Mexico.

Progress on Goal #8: Co-I Klinglesmith and New Mexico Tech have sponsored 34 star parties during the reporting period with over 1400 people in attendance. Co-I Butcher served as a project mentor for a two-person female high school team that entered a project in the prestigious Siemens Competition. Their project involved taking astronomical measurements of potentially dangerous Near Earth Asteroids, calculating their orbits, and then designing spacecraft missions for deflection of those asteroids by using one of several proposed technologies to alter their orbits in a specific way such that they no longer pose a risk of collision with Earth. Both team members graduated and were accepted into prestigious universities to study astrophysics.

Systemic change as evidenced by:

Improvements in jurisdiction research and development infrastructure: See progress on Goal #4 above.

Increased financial commitment from the jurisdiction, industry, and participating institutions: None

Response of activities to NASA and jurisdiction priorities: None

Reordered jurisdiction and/or institutional priorities: None

Examples of successful technology transfer to the private sector: None

Extent to which collaborations with jurisdiction agencies, industry, research and academic institutions, and NASA have evolved.
In the area of spacecraft navigation about small bodies, the NMSU researchers have interacted at the Spaceflight Mechanics Conference with Drs. Shyam Bhaskaran and Roby Wilson of NASA/JPL. Prof. Scheeres has maintained his close interactions with several additional NASA and industry colleagues. In addition, Dr. Sanyal was awarded the Summer Faculty Fellowship to spend summer 2012 at the Air Force Research Laboratory (AFRL) working with collaborators Lovell and Jah on issues tangentially related to the project. Dr. Butcher also recently visited AFRL and gave a talk on spacecraft delayed feedback attitude control and estimation, and he expects to return to AFRL later this summer for another invited seminar. Sanyal has recently developed collaborations at NASA Ames which resulted in a submitted proposal. Also, both NMSU and CU are participating institutions in the FAA COE on Commercial Space Transportation.

Discussion of interaction between and cooperation with the jurisdiction's Space Grant Consortium.
New Mexico Space Grant continues to provide funding to Dr. Amit Sanyal for the support of select students.

Research success of individual investigators as measured by:

Articles submitted to or published in refereed journals

Nazari, M., Samiei, E., Butcher, E. A., and Schaub, H., "Attitude Stabilization using Nonlinear Delayed Actuator Control with an Inverse Dynamics Approach," *Journal of Guidance, Control, and Dynamics*, in press.

A. Sanyal, J. Bohn and A. M. Bloch, "Almost Global Finite Time Stabilization of Rigid Body Attitude Motion," submitted to IEEE Transactions on Automatic Control.

Lee, D., Sanyal, A., K., and Butcher, E. A., "Almost Global Asymptotic Tracking Control for Decentralized Spacecraft Formation Flying," *Journal of Guidance, Control, and Dynamics*, submitted.

Lee, D., Bang, H., Butcher, E. A., and Sanyal, A. K., "Coupled Position and Attitude Control of a Spacecraft in the Proximity of a Tumbling Target," *Acta Astronautica*, revision submitted.

Lee, D., Bang, H., Butcher, E. A., and Sanyal, A. K., "Nonlinear Output Tracking and Disturbance Rejection for Autonomous Close Range Rendezvous and Docking of Spacecraft," *J. of the Astronautical Sciences*, revision submitted.

J. Castorena and C.D. Creusere, "Sub-Nyquist sampling of sparse signals using overlapping windows: RIP Bounds," submitted to *IEEE Transactions on Signal Processing*, August 2012.

Hanowell, J. (2013), "Photometric Analysis of 4611 Vulkaneifel, *submitted Minor Planet Bulletin*

Klinglesmith III, D. A. (2012), "Asteroid lightcurve analysis at the Etscorn Campus Observatory for January and Feburary 2012", *Minor Planet Bul.* ,**39-3, *109-110***

Klinglesmith, D. A., Hanowell J., Risley, E., Turk, J., Vargas, Warren, C. A., (2013), "Etscorn Observed Asteroids: Results for six Asteroids, December 2012 – March 2013", *submitted Minor Planet Bulletin,*

Klinglesmith III, D.A., Risley, E., Turk, J., Vargas, A., Han, X. L., Heffner, O.R., Kidd, A.W., Magnetta, B.J., Rastede,F.W. (2012), "8077 Hoyle: A Short Period Asteroid ", *Minor Planet Bul*., **39-4**, 203

Klinglesmith III, D.A., Ferrero, A., Odden, C., Strabla, L., Quadri, U., Girelli, R. (2012), "Light Curve for 8345 Ulmerspatz", *Minor planet Bul.*, **39-4**, 204-209

Klinglesmith III, D.A., Risley, E., Turk, J., Vargas, Warren, C. A. Ferrero, A., (2013), " Lightcurve Analysis of 3948 Bohr and 4874 Burke: An international Colaboration", *Minor Planet Bul*., **40-1**, 15-16

Klinglesmith III, D.A., Risley, E., Turk, J., Vargas, Warren, C.A., (2012), “Lightcurves for 1394 Algoa, 3078 Horrocks, 4724 Brodken and 6329 Hikonejyo”, *Minor Planet Bul.,* **40-1**, 16-17

Klinglesmith III, D. A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C. A., (2013), “Asteroid Synodic Periods from Etscorn Campus Observatory”, **40-2,** 65-66

Li, B., Zhao, H., Han, X.L., Klinglesmith III, D.A, Hanowell, J., (2013), “Photometric Observations of 1542 Schalen”, *Minor Planet Bul.,* **40-2**, 68-69

Pilcher, F., Benishek, V., Ferrero, A., Klinglesmith III, D. A., Pravec, P., Roy, R., Behrend, R., (2013), “New Photometry of 1473 Ounas”, *submitted Minor Planet Bul*.,

Pilcher, F., Briggs, J.B., Franco, L., Inasaridze, R.Y., Krugly, Y.N., Molotov, I.E., Klinglesmith III, D.A., Pollock, J., Pravec, P. (2012), “Rotation Period Determination for 5143 Heracles *“, Minor Planet Bul.,* **39-3,** 148-151

Pilcher, F., Benishek, V., Briggs, J.W., Ferrero, A., Klinglesmith III, D. A., Warren, C. (2012), “Eight Months of Lightcurves of 1036 Ganymed”, *Minor Planet Bul.,* **39-3**, 141-144

Risley, E., (2013), “3382 Cassidy: A short Period Asteroid”, *Minor Planet Bul., **40-2,*** 80-81

Turk, J., (2013), “Lightcurve for 5275 Zdislava”, *Minor Planet Bul.,* **40-2**, 67

Vargas, A., (2013), “Synodic Period for “2454 Olaus Magnus from Frank T. Etscorn Observatory”, **40-2,** 61

Warren, C. A., (2012), “ A Determination of the Rotational Period of 8882 Sakaetamura”, *Minor Planet Bul.,* **39-4**, 206-207

Warner, B.D., Klinglesmith III, D.A., Skiff, B.A. (2012), “Lightcurve Inversion for 47035 (1998WS)”, Minor planet Bul., **34-4**, 216-220

S. Tardivel, P. Michel, and D.J. Scheeres. “Deployment of a lander on the binary asteroid (175706) 1996 FG3, potential target of the European MarcoPolo-R sample return mission,” *Acta Astronautica*, in press, 2013.

S. Tardivel and D.J. Scheeres. “Ballistic Deployment of Science Packages on Binary Asteroids,” *Journal of Guidance, Control and Dynamics*, in press, 2013.

Talks, presentations, or abstracts at professional meetings

Nelson, E., Creusere, C.D., Critz, T., and Butcher, E., “Analysis of Communication Rates in the Proximity of Near-Earth Asteroids,” Proc. International Telemetering Conference, Oct. 2013, Las Vegas, NV.

L. Holguin, A. Sanyal and S. P. Viswanathan, ``Guidance and Control for Spacecraft Autonomous Rendezvous and Proximity Maneuvers using a Geometric Mechanics Framework," AIAA Guidance, Navigation and Control Conference, August 13-16, 2012, Minneapolis, MN.

S. P. Viswanathan, A. Sanyal and L. Holguin, ``Dynamics and Control of a Six Degrees of Freedom Ground Simulator for Autonomous Rendezvous and Proximity Operations of Spacecraft," AIAA Guidance, Navigation and Control Conference, August 13-16, 2012, Minneapolis, MN.

J. Bohn and A. Sanyal, ``Unscented State Estimation for Rigid Body Motion on SE(3)," 51st IEEE Conference on Decision and Control, December 10-13, 2012, Maui, HI.

Nazari, M., Butcher, E. A., and Hall, C.D., "On the Stability Investigation of Single- and Dual-Spin Spacecraft," 2012 AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, Aug. 13-16, 2012.

D. Lee, S. P. Viswanathan, L. Holguin, A. K. Sanyal and E. A. Butcher, "Decentralized Guidance and Control for Spacecraft Formation Flying using Virtual Leader Configuration," to be presented at American Control Conference, June 17-19, Washington DC, 2013.

Lee, D., Butcher, E.A., and Sanyal, A., "Sliding Mode Control for Decentralized Spacecraft Formation Flying using Geometric Mechanics," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Lee, D., Sanyal, A. K., Butcher, E. A., and Scheeres, D. J., "Spacecraft Hovering Control for Body-Fixed Hovering over a Uniformly Rotating Asteroid using Geometric Mechanics," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Nazari, M., Butcher, E. A., and Mesbahi, A., "On Control of Spacecraft Relative Motion in the Case of an Elliptic Keplerian Chief," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

Nazari, M., Wauson, R., Critz, T., Butcher, E. A., and Scheeres, D. J., "Observer-Based Body-Frame Hovering Control over a Tumbling Asteroid," 2013 Astrodynamics Specialist Conference, Aug. 11-15, Hilton Head, SC.

M. Izadi, J. Bohn, D. Lee, A. K. Sanyal, E. Butcher, and D. J. Scheeres ``A Nonlinear Observer Design for a Rigid Body in the Proximity of a Spherical Asteroid," to be presented at ASME Dynamic Systems and Control Conference, Oct 21-23, Stanford, CA.

C.D. Creusere, E. Nelson, T. Critz, and E. Butcher, "Analysis of communication interconnectedness in the proximity of near-earth asteroids," *International Telemetering Conference Proceedings*, October 2012.

Castorena, J.; Creusere, C.D., "Compressive sampling of LIDAR: Full-waveforms as signals of finite rate of innovation," *Signal Processing Conference (EUSIPCO), 2012 Proceedings of the 20th European* , vol., no., pp.984,988, 27-31 Aug. 2012.

Castorena, J.; Creusere, C.D., "Random impulsive scan for lidar sampling," *Image Processing (ICIP), 2012 19th IEEE International Conference on* , vol., no., pp.365,368, Sept. 30 2012-Oct. 3 2012.

Erik Komendera, Daniel Scheeres and Elizabeth Bradley, "Intelligent Computation of Reachability Sets for Space Missions," IAAI conference on Artificial Intelligence, Toronto, CA, July 22-26, 2012.

Erik Komendera, Elizabeth Bradley and Daniel Scheeres, "Efficiently Locating Impact and Escape Scenarios in Spacecraft Reachability Sets," 2012 AIAA Astrodynamics Specialists Conference, Minneapolis, MN, Aug. 13-16, 2012.

D.A. Surovik and D.J. Scheeres. "Computational Efficiency of Symplectic Integrators for Space Debris Orbit Propagation," paper presented at the AIAA/AAS Astrodynamics Specialist Meeting, Minneapolis, August 2012.

D.A. Surovik and D.J. Scheeres. "Adaptive Envisioning of Reachable Mission Outcomes for Autonomous Navigation at Small Bodies," paper to be presented at the AAS/AIAA Astrodynamics Specialist Meeting, Hilton Head, South Carolina, August 2013.

<u>Articles submitted to NASA venues</u>

None

<u>Patents and patent applications</u>

None

<u>Follow-on grant proposals submitted/funded including funding amounts</u>

C.D. Creusere and D. Voelz, *Pulse complexity based LIDAR scene modeling for sparse reconstruction and super-resolution*, National Geospatial Intelligence Agency, $150,000, Dec. 2012-Dec. 2014 (plus 3 option years at $75,000/year).

Amit Sanyal: "Stable Control of Small Spacecraft using Geometric Mechanics" was submitted to the National Aeronautics and Space Administration on June 5, 2013. It was submitted to the NASA Small Spacecraft Technology Program in collaboration with NASA Ames Research Center.

Daniel Scheeres: Two funded proposals from the NASA NSTRF program.

Participants

Faculty

Dr. Eric A. Butcher, New Mexico State University
Dr. Amit K. Sanyal, New Mexico State University
Dr. Charles D. Creusere, New Mexico State University
Dr. Daniel J. Scheeres, University of Colorado Boulder
Dr. Daniel A. Klinglesmith III, New Mexico Institute of Mining and Technology

Post-doctoral, graduate, and undergraduate students supported from EPSCoR funds

Dr. Daero Lee, postdoc, New Mexico State University
Evan Nelson, Ph.D. student, New Mexico State University
Morad Nazari, Ph.D. student, New Mexico State University
Jan Bohn, Ph.D. student, New Mexico State University
Maziar Izidi, Ph.D. student, New Mexico State University
Thomas Critz, M.S. student, New Mexico State University
Robert Wauson, M.S. student, New Mexico State University
Juan Acosta, M.S. student, New Mexico State University (underrepresented/minority student)
Ethan Risley, undergraduate, New Mexico Institute of Mining and Technology
Janek Turk, undergraduate, Mexico Institute of Mining and Technology
Angelica Vargas, undergraduate, Mexico Institute of Mining and Technology
Simon Tardivel, Ph.D. student, University of Colorado
Samantha Rieger, Ph.D. student, University of Colorado

Students working on aspects of current project who are supported through other sources

Lee Holguin, M.S. student, New Mexico State University
Sashi Vishwanathan, M.S. student, New Mexico State University
Jesse Hanowell, undergraduate student, New Mexico Tech
Curtis Allen Warren, undergraduate student, New Mexico Tech
David Surovik, Ph.D. student, University of Colorado