Proposal to the

International Space University 2010 Space Studies Program

for a Technical Project on an

Asteroid Mining Mission

Respectfully Submitted

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Abstract

Asteroid Mining promises the potential of tremendous return economically and scientifically. Radar albedo data indicate that some near earth objects (NEO) appear to consist of thousands of tons of platinum family metals (iridium, osmium, and palladium) potentially worth billions or trillions of dollars at market. As great as the potential reward may be, the challenge of deploying a resource extraction mission to an asteroid, operating it successfully, and returning the bounty and the crew to the earth may prove even greater.

This proposal for a Technical Project at the ISU 2010 summer Space Studies Program will address this challenge. This study project will decompose the challenge of asteroid mining into the key areas:

- Economic viability and commercial partnerships,
- International partnerships and treaty obligations,
- Launch vehicles, orbital mechanics and trajectory design,
- Mission design and operations, and
- Mining technology for "*mini*gravity" and vacuum operations.

The expected outcomes of this project include an assessment of whether asteroid mining is economically, politically, and technologically feasible with a design concept for mining a candidate metallic asteroid. The design concept serves as a test case for the feasibility assessment.

Introduction

Asteroid prospecting and mining has been one of the signature concepts of exploration virtually since the beginning of the Space Age. The economic imperative to find some way to make a profit from space resources has always been an important driver, even if it was not as visible as strategic and scientific considerations. FIGURE 1 shows the cover of the July 1961 *Analog* proclaiming the future of asteroid mining by 1995. The spacecraft number 271 bears the trade name "Astrosteel Corp." Although the time table for mining has not been nearly as aggressive as the article in *Analog* predicted, there has been some progress.

In the decade and a half preceding SSP 2010, the space community has been acquiring knowledge and experience in the design and operation of asteroid and comet missions. There are two classes of these missions: one way and sample return. TABLE 1 shows the highlights of some of these sample return missions: proposed, planned, and implemented. The two sample return missions completed to date are NASA's Stardust and Genesis missions, returning cometary particles and solar wind particles, respectively.

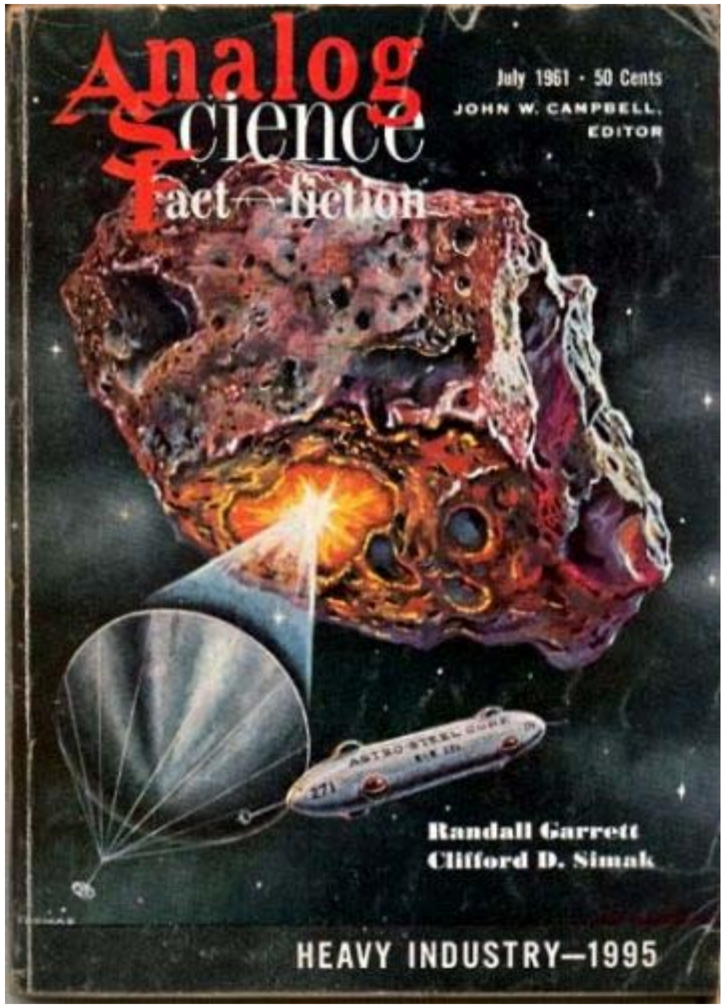

FIGURE 1. Cover of ANALOG, July 1961 showing an iron mining and steel-smelting operation in space at an unspecified asteroid. Art Credit: Gene Thomas. http://www.sfcovers.net/Magazines/ASF/ retrieved 21 Sept 2009.

Asteroid Sample Return

The next mission to return will be JAXA's Muses-C Hayabusa, which will return samples from the asteroid Itokawa. FIGURE 2 shows the complexity of the orbital mechanics and trajectory design to rendezvous with the asteroid Itokawa and return to the earth. FIGURE 3 shows a detailed image of Itokawa taken by Hayabusa, with colored ellipses showing the various sites where the mission plan was to collect samples.

Human Asteroid Mission

The past four years have seen a growing interest in a human mission to an asteroid (Asaravala, 2005) Couvault, 2008; David, 2006; Kleisius, 2008). Some of the human asteroid mission concepts are provocative and worthy as an introduction to this area of interest. FIGURES 4a to 4c show a concept that DigitalSpace portrayed in support of the early NASA concept for a crewed asteroid mission.

TABLE 1. Proposed, Planned, and Implemented Asteroid and Comet Sample Return Missions.

Name	**Organization/ Agency**	**Nation**	**Date of Launch**	**Target Body**	**Sample Sought**	**Landing Site**	**Return Date**	**Return Restriction**	**Status**
Stardust	JPL-NASA	USA	6 FEB 1999	Comet Wild-2	Comet & Interstellar Particles	Utah UTTR	15 JAN 2006	None	Completed
Genesis	JPL-LANL-NASA	USA	8 AUG 2001	Sun, from L1 Point	Solar Wind Particles	Utah UTTR	8 SEPT 2004	None	**Completed**
MUSES-C / Hayabusa	ISAS / JAXA	Japan	18 JUNE 2003	SF36 Itokawa	Impact ejecta	Woomera, Aus.	2010	None	In Flight
Phobos-Grunt	Lavochkin	Russia/ ESA	TBD	Phobos Sample Return	Regolith	Russia, TBD	TBD	TBD	In Planning
Comet Nucleus Sample Return	Langley Research Center / NASA	USA	TBD	Comet Brooks-2 Wirtem, Kopff, orTritton	Frozen comet core	TBD	TBD	TBD	Under study
Hera	Arkansas-Oklahoma Center	USA	TBD	3 Asteroids of different types	Variety of surface materials	TBD	TBD	None	Proposed
Aladdin	Space Research Institute	Russia	TBD	Main Belt Asteroid	Impact ejecta	Russia, TBD	TBD	None	Proposed
OSIRIS	University of Arizona	USA	TBD	RQ36	Carbonaceous material	TBD	TBD	None	Proposed
Manned Mission	NASA	USA	TBD	2000SG344	All types	TBD	TBD	None	Under Study

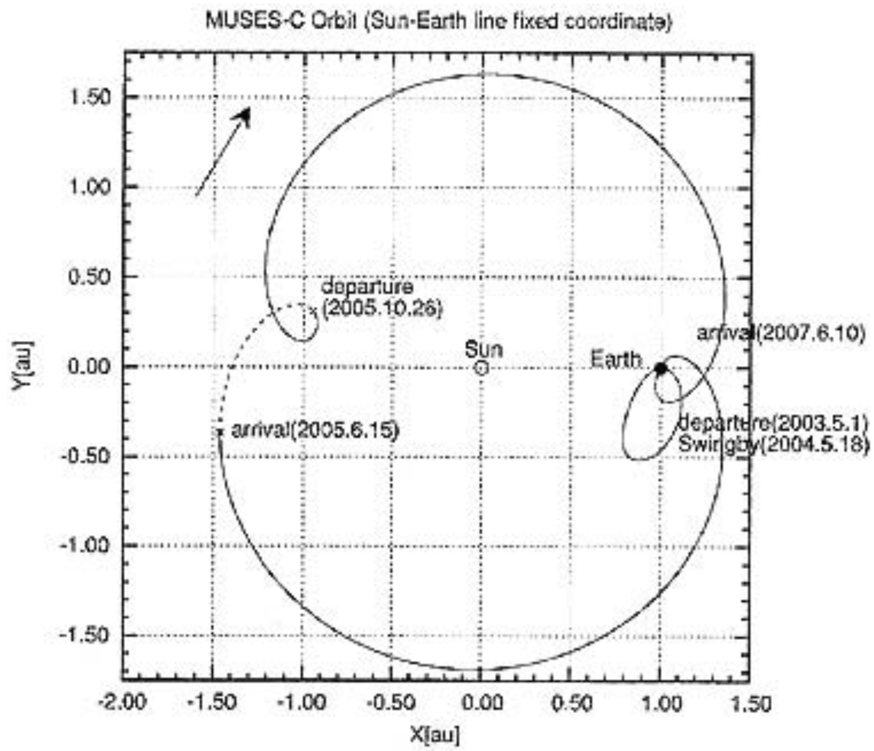

FIGURE 2. Original trajectory design for the Hayabusa mission. Credit ISAS. http://www.isas.ac.jp/e/special/2003/kawaguchi/02.shtml, retrieved 4 SEPT 2009.

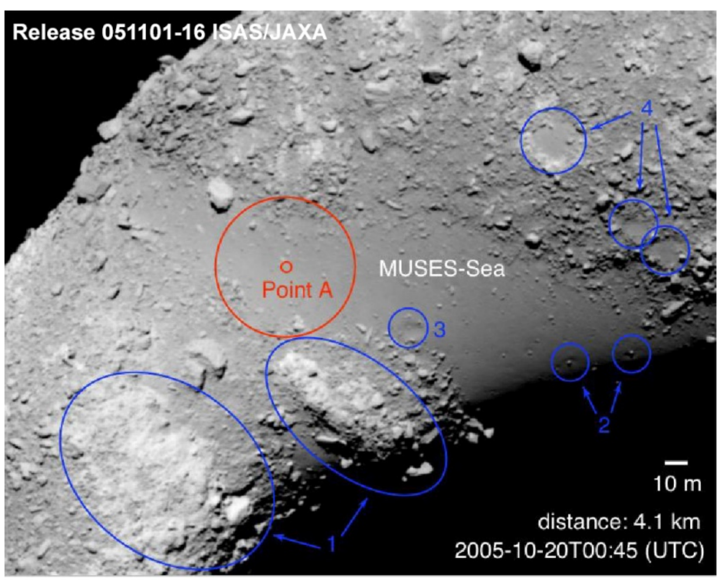

Fig. 11 MUSES-SEA Area, Site candidate-A. Mountains, Boulders and Dimples, Craters.

FIGURE 3. Hayabusa image of the MUSES-Sea on asteroid Itokawa. Credit ISAS/JAXA. Courtesy of the Planetary Society. http://www.planetary.org/news/2005/1102_Hayabusa_Japans_Asteroid_Mission.html retrieved 4 SEPT 2009.

FIGURE 4a. Orion with a mission/lander module approaches a generic asteroid. The white Service Module is oversized compared to the LEO version so that it can carry the greater quantity of propellant and consumables to support the crew throughout the longer mission.

FIGURE 4b. Orion with mission/lander module makes a touchdown on the surface of an asteroid, lofting dust in the process. The icon in the upper right corner represents a symbology for safety status.

FIGURE 4c. EVA crewmembers translating around the mission/lander module while its robot arm drills into the regolith. This mission module would include an EVA airlock. Notice the landing blast pattern in the asteroidal dust.

Images by permission of Bruce Damer, President, DigitalSpace. Posted 30 JULY 2007 to http://www.digitalspace.com/projects/neo-mission/index.html, retrieved 4 SEPT 2009.

Asteroid Selection

The SSP10 Call for Proposals mentions 3554 Amun as a potential mining target. John Lewis, in his book Mining the Sky (1995), calculated the market value of the mineral content of 3554 Amun at $20 trillion. However, more precise and recent observations of the radar albedo of 3554 Amun indicate that it may not be metallic (Wikipedia, 3554 Amun, http://en.wikipedia.org/wiki/3554_Amun, retrieved 2 SEPT 2009).

An alternative to Amun *may* be 1986 DA (Ostro, et al, 1991), with a more substantially proven radar albedo indicating metallic content. Ostro, et al reported an estimated 100,000 tons of gold and platinum-family metals, estimated at the time to be worth $1 trillion. 1986 DA has a much lower inclination but a longer orbital period than 3554 Amun. For both targets, the launch, rendezvous, and return opportunities will play a crucial role in determining economic and operational viability.

Thus, many factors go into selecting a target asteroid besides estimates of the size and value of their metallic composition. TABLE 2 shows a comparison of Itokawa, 1986 DA, and 3554 Amun to illustrate the differences in physical properties, orbital parameters, and requirements for rendezvous deltaV. The key discriminators may prove to be the orbital inclination, which is a first order indicator of the deltaV requirement and the orbital period, which dictates launch and return windows for lowest energy Hohmann transfer trajectories. The numbers for DeltaV are nominal order of magnitude estimates based on the Shoemaker equation used by Echo.JPL.

TABLE 2. Comparison of the Salient Properties of Three NEO Asteroids

Property	**35143 Itokawa SF 36**	**1986 DA**	**3554 Amun 1986 EB**
Orbit-crossing	Apollo-type earth-crosser with most of its orbit outside the earth's, Mars-crosser.	Mars-crosser, Amor-type: approaches earth orbit but does enter within it.	Aten-type earth-crosser with most of its orbit within the earth's, Venus-crosser.
Aphelion (AU)	1.695 AU	4.457 AU	1.247 AU
Perihelion (AU)	0.953 AU	1.161 AU	0.701 AU
Semi-Major Axis	1.324 AU	2.809 AU	0.974 AU
Orbital Period	556.355 days	1719.466 days	350.964 days
Rotation Period	12.13 hours	3.57 hours	2.53 hours
Largest Dimension	0.535 km	2.3 km	2.5 km
Inclination from the Ecliptic Plane	1.622 degrees	4.310 degrees	23.263 degrees
Comparative DeltaV to rendezvous from earth (Echo.JPL)	4.632 km/sec	7.144 km/sec	10.246 km/sec

The student teams will analyze these data and compare metallic asteroids with mining potential to select a target. FIGURE 4 shows the orbit of 3554 Amun in relation to the ecliptic and earth's orbit. The difficult of staging repeatable missions to 3554 Amun on a regular schedule should be self evident from this difference in inclination.

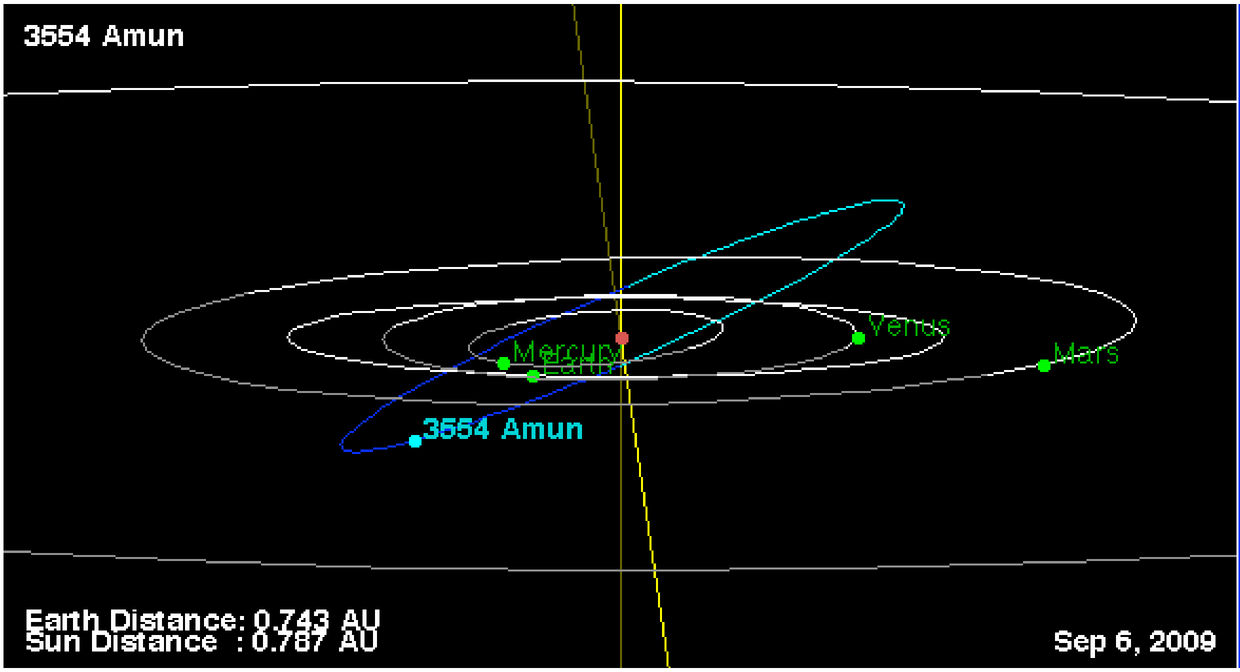

FIGURE 4. Orbital diagram for 3554 Amun showing its 23 degree tilt out of the ecliptic plane. Earth, labeled in green, appears right in front of Mercury. (Retrieved from the NASA JPL Small Body Database Browser, 6 SEPT 2009).
http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=3554%20Amun;orb=1;cov=0;log=0;cad=0#orb

Asteroid Mining

The advocates of asteroid mining offer little evidence to substantiate their extravagant claims for *profit* from this vast wealth just waiting for exploitation. Or, to paraphrase Patrick O'Brian (from the Aubrey-Maturin novels), the anticipation of gaining sudden great wealth has caused far more insanity than the loss of it. Thus, these kinds of estimates of vast, sudden wealth always evoke a sense of caution if not outright skepticism. One area that demands the most attention is the technology to extract and process metals in the vacuum of space and the *mini*gravity of an asteroid. It will be a major challenge to the TP teams to put together a case for economically and technically feasible asteroid mining.

Interdisciplinary Approach to Teaching

The technical project takes a multidisciplinary approach to leading the class effort. The key disciplines are economics, political science, engineering, operations, and space architecture. The opportunity this class presents is to facilitate these diverse specialties to work together on an exciting project that will stretch all team members' abilities to their limits; the goal is to introduce a process whereby they can learn to work together with trust and effective communication in a time-efficient and technically accurate manner.

Observations from SSP 09

Having participated in SSP 2009 at in the Mars Caves Projects, the proposer made several observations that figure in the drafting of this proposal.

1. The students did not begin thinking about the *scope* of the deliverables (design, analysis, or recommendations) until very late in the three projects. Consequently, in the midterm and final presentations, it was not always clear what they were

actually recommending. For example, the DREAM project for disaster preparedness in Belize mentioned "mitigation" many times, but they had few specifics to offer. It was never clear that they were only providing satellite data, and in fact were not addressing any mitigation at all.

2. The students confounded the Work Breakdown Structure (WBS) with the organizational chart. It is essential for the students to go through the process of democratically setting up their organization to execute the project and to assign members to each of the roles. However, it is a less essential and efficient use of the students' limited time to develop the design problem decomposition from scratch that the represents. Therefore, the proposer provides an outline WBS to give the students a jump-start on organizing the project. They will be free to modify the WBS as they progress.

Faculty Structure

The faculty structure will consist of a partnership between three technical experts and the students. The students will bring much of the expertise to the class, but there are a few critical areas for this mission where, to ensure a successful outcome and efficient use of the students' time, the faculty will provide some of the necessary expertise. These proposed experts provide the unique and sophisticated capabilities that we cannot expect from the students:

- Orbital mechanics and trajectory design (Warren James, Northrop Grumman)
- Robotic mining technology (Kris Zacny, Honeybee Robotics)

That said, the students take responsibility for organizing the development and execution of the project. The faculty will be available to advise and consult as needed, and to give guidance on how to proceed from one hurdle to the next.

Pedagogy

The TP starts about six weeks after intensive academic study and exams. The pedagogy for the Asteroid Mining TP takes a different and hopefully refreshing approach. Lectures will keep to a minimum; the classes will follow a preceptorial discussion format. The teacher questions the students to spark discussions about the key aspects of the subject or problem at hand. These classes will challenge the students to apply their natural curiosity, analytical skills, and creativity to synthesize the subject matter into an overarching construct.

Introductory Exercises

Based upon consultation with the ISU faculty and administration, and in consideration of the SSP's progress to the time the Technical Projects commence, we will select a set of kickoff exercises for the team. The TP team will go through a series of introduction exercises and then a design exercise. Depending upon the number of students from each discipline who sign up for the Asteroid Mining TP, we will establish the group size in which they make the introductions. Team members will make introductions both within their discipline group and in an interdisciplinary group. In the ***introduction exercises,*** each team member will:

1. Introduce himself or herself in his or her own words. Describe background including education and technical/scientific expertise or specialization.
2. Describe what she or he *offers to* the other team members in terms of information, analysis, data, evaluation, and integration.

3. Describe what she or he *needs from* the other team members in terms of information, analysis, data, evaluation, and integration.
4. Explain what she or he believes constitutes "proof:" what is credible, reliable, or persuasive analysis, data, evaluation, or design.

The ***design exercise*** will bring the team's attention to bear early in the project upon the design problem of a mission to an asteroid. The purpose is to get the students talking and thinking about the big picture early in the process, and to give them the first-hand cognizance of reporting-out their deliverables. Given a foundation of the essential data, they will perform this one- to two-day exercise without resort to digital props. They will need to think on their feet, and hand-write their bullets on flip charts, draw their designs freehand, and above all engage with one another.

Syllabus

Upon acceptance of this proposal, the offeror will prepare a syllabus that describes the specific activities of the course. The syllabus includes the description of lectures and preceptorial discussions, schedule, and milestones. The proposer expects to interact with the students in all the subject and discipline areas of this proposal.

Design Methodology for the Project

One of the most daunting aspects of this Technical Project is how to bound the design problem space. The difficulty lies in making it neither too narrowly focused upon operations around an asteroid nor too broad and diffused to accommodate all the possible space economics, design, engineering, logistics, operations, politics, and transportation scenarios. This scoping of the project will emerge as the central decision-making process for the students in concert with their faculty advisors.

Design Problem Definition as a Social Agreement

The first principle is that the design problem definition exists only insofar as the participants can agree to what it is. In this kind of participatory design project, the problem definition emerges as a kind of social contract among the participants. Involvement in a participatory project invokes obligations that are not typically part of the normal work or school environment. Naturally, there will be robust discussions, intellectual differences of opinion, and heart-felt disagreements. Yet, the project can succeed only insofar as the team members can forge agreements about what this social contract includes. Then, they must find a balance between big ideas and compromising with the tyranny of reality.

The Symmetry of Ignorance

The second principle is the "symmetry of ignorance." Everyone on the team knows less about *some* of the key areas than the other members of the team. Therefore, the recognition that nobody can know it all should help the team members value what their colleagues do know and what they can contribute. Understanding the symmetry of ignorance can engender respect, communication, and cooperation among participatory design members.

Multidisciplinary Interaction as Process and Outcome

The third principle is multidisciplinary interaction among the student teams; it constitutes one of the most important outcomes of the Technical Project. There will be many areas of overlap and claims to the same content area. The design method this class will apply is that when there are multiple claims to a content area, it is recognition of the importance of that topic. It will not be an invitation to make an *a priori* division to allocate it to one team or another to "avoid duplication of effort." Not until the two or more teams making the claims work through their discussion, will they make a decomposition of the topic and assign the results to one or more teams. Conversely, if no discipline team claims a particular area, that calls for a new understanding of why not and reconsideration of whether it is necessary.

The Five Main Subject Areas

Students' teams focusing on each of the five main subject areas will confront profound and fundamental problems that may require changes to existing approaches and practices so that an asteroid mining mission can succeed.

Economic Viability and Commercial Partnerships

Proving the economic case -- and under what partnership and financing arrangements it may be viable -- is the challenge to this team. The stark cost reality is that if 100 percent pure gold bars existed naturally on the moon, stacked on pallets, ready to be picked up and returned to the earth, it would not be profitable. The cost of the round trip transportation from the moon's gravity well would exceed the market value of the gold.

An asteroid mining mission may offer the prospect of becoming profitable if it is possible to control the return propulsion and other mission design and operations costs. There are principally five ways to achieve this cost reduction:

1. Minimize the number of different parts and interfaces,
2. Use existing production hardware with a minimum of new major parts,
3. Reduce the mass or the propellant needed to move the mass,
4. Minimize the gravity well to overcome for transporting crew and cargo, or
5. Find ways to use the products in space so that it is not necessary to return them to LEO or the earth.

The economics team will develop a model that accounts for these variables as a way to determine which mission designs are feasible and better still profitable. They will propose a model for the commercial partnership that can make asteroid mining viable.

International Partnerships and Treaty Obligations

Current space treaties state that the cosmos belongs to everyone; therefore the resources of the cosmos belong to no one. The shortcoming of this vestige of the 1960s should be obvious: exploration and development of space beyond LEO and certainly beyond the earth-moon system will depend on our ability to extract, process, and use the resources we find. Call it unfair exploitation of resources or call it investment in a permanent presence in space – the simple answer is the companies or agencies that take the risk will reap the benefits. However, that appeal to pure capitalism does answer the aspirations and interest of the "have-nots" on earth who may wish to share in the rewards.

The students on this team will address the specific language of the ruling treaties to propose alternative clauses that will allow and encourage asteroid mining. The building of international partnerships follows upon this removal of impediments. The students will propose a model for the international partnership that will be inclusive insofar as any country that wants to participate may do so. This model should go beyond "pay to play;" it will look at ways in which countries with specific skills, capabilities, or resources can contribute. In some cases, the international (and the commercial) partnership may make investments in developing countries so that they can grow into a position to participate in later mining missions or operations.

Launch Vehicles, Orbital Mechanics, and Trajectory Design

The "conventional wisdom" concerning asteroid, comet, and other small body missions: *when* you launch determines *where* you can go. Conversely, *where* you want to go dictates w*hen* you must launch. 3554 Amun adds the complexity that its orbit is tilted about 23 degrees out of the ecliptic plane, further limiting potential conventional launch windows, since it passes close to the earth's orbit at only two loci. These spatial-temporal constraints for launch and return dates will bring far-reaching implications to a mining operation. However, if the transportation system includes logistics and staging depots in geosynchronous orbit or the LaGrangian points, it may be possible to decouple the schedule of transits to the asteroid from the launch and return to earth.

A round trip mission to an asteroid to extract valuable resources may return them to any of several destinations: to the earth, to a mid-point station such as a LaGrangian point, geosynchronous orbit, the surface of the moon, Phobos, or Mars. Once the space community develops the capability to support and operate spacecraft beyond low earth orbit (LEO) and throughout the earth-moon-NEO system, it becomes possible to supply these stations with the resources to build and grow. It leads to establishing a trade economy among these extraterrestrial bases and with the earth itself.

Mission Design and Operations

The Mission design and operations problem space is the largest of the five main topics, recreating many of the classic issues of spaceflight design. The first question is the allocation of functions between machines and humans:

- What do humans do, and from where do they do it?
- What do robots do?
- What degree of supervision does the crew exert over the robots?
- What degree of automation is required for both crewed and uncrewed undertakings?

Assuming that the asteroid mining mission is a credible opportunity within the next 10 to 15 years, the level of automation and robotics *reliably* available then will differ little from what is available today. Therefore, if the mining operations require real time or monitoring of activities or direct teleoperations, there must be a human crew on station at the asteroid. Therefore, the mission includes both human and robotic spacecraft; space-suited humans will perform extravehicular activities alongside robotic mining equipment that are spacecraft in their own right.

The team will select a design for the crewed vehicle to take the crew to the asteroid, and any additional modules or systems to help support and sustain the crew while they work there. The team will provide for the return of crew and the products of mining. The only element that does not return is the robotics, except in rare cases to analyze wear and tear or failure.

*Mining Technology for "***Mini***gravity" and Vacuum Operations*

On earth, what makes mining economical for most rare or precious metals is the availability of water in vast quantities to process the excavated material. Panning for gold is the classic example. In an industrial setup, large sluices, sluice boxes, and settling chambers process the ore to extract the gold nuggets and dust that is thousandths of the mass of the original bulk material. In space, water is not available for this purpose unless the mining operation brings it. On earth, the economic geography is different. It is common to transport unrefined iron or bauxite ore hundreds or thousands of kilometers in railway cars or ships to the smelter. In space, there is no such waypoint, close to the source of anthracite coal for smelting iron to make steel. In space mining, it will not be economic to transport unrefined ore. The refining must occur at the point of extraction in deep space so that the returned commodity is the lowest mass for highest market value.

The asteroid mining operation will need new technology for drilling, moving material, and refining it in situ. Drilling in a vacuum poses a host of challenges, not the least of which is how to cool the drill bit so it does not melt from its own friction. On earth, a constant supply of water can remove both heat and debris. Similarly, the drilling and excavating motors need cooling. The team will identify and analyze these kinds of technology and operational issues, and find potential solutions for asteroid mining. The availability of these technical solutions will test the feasibility of the Project.

Work Breakdown Structure

The WBS serves as a content guide to the project. It differs from a management organizational chart because the WBS does not say anything about who does which part of the work or who has oversight for which parts. The WBS simply states the work that the team needs to do. It is their responsibility to assign themselves to do it. TABLE 3 shows this WBS. Given that each team member will serve on one of the five discipline topics, *one* approach would be for every team member to do a task within each of the five major headings: Research, Problem Definition, Concept Development, Concept Selection & Refinement, and Documentation & Presentation.

This approach to the WBS establishes the five areas of work that are independent of the team discipline structure. These WBS tasks are not necessarily sequential or linear. Rather, the discipline teams may need to move freely among the parts of the WBS as they develop their ideas and test them against the constraints. Within this design methodology, a concept can serve as a hypothesis about what the problem is; the research results inform the selection and refinement of concepts.

Research

We have seen over 50 years of development of space science, space policy, and space technology since the birth of the Space Age. While it is not reasonable to expect the students to learn all of it (alas, even in their own fields), it is vital for them to find and process the significance of these developments for the Asteroid Mining Project. At a minimum, this research should enable the students to avoid wasting time “reinventing the gyroscope wheel.” What is more important, the students can find ideas and precedents that they apply to craft a solution.

Problem Definition

Problem definition is the fulcrum of the design methodology. The students examine and compare their understanding of the project and its challenges. Their ability to forge an agreement upon what is the problem serves as the gateway to project success. Because the asteroid mining mission is a multivariable problem with many possible outcomes, it will be especially difficult to arrive at a simple, well-structured problem definition. It may be necessary to find a galvanizing principle in this condition of irresolution that may not satisfy every objective but that allows for mission success.

Concept Development

Concept Development is the main opportunity for the students to express and apply their creativity. They go through a series of initiatives to explore alternative paths and options to mission success. The approach to concept development will be to articulate requirements and constraints, and seek solutions that fit the parameters. During this phase, the emphasis is on generating alternatives while holding off on critiquing the ideas. However, this effort does not presuppose "brainstorming" or other forms of scattershot subjectivity. It would be far better for the team to postulate a systematic method of defining the concepts that affords a logic-based selection process.

Concept Selection, Integration, and Refinement

In this area of the WBS, the students and faculty within each discipline team evaluate the sets of options they generated, based on evaluation criteria from the faculty. Then, multidisciplinary teams comprised of representatives of each discipline evaluate these options from their "outside" perspective. The selection process links together the highest-rated options from each of the disciplines, however there is no guarantee that they are compatible or even make sense together.

That is where integration and refinement play their roles. The second- or third- best option in one discipline may prove the key to allowing the top-rated options from all the other disciplines succeed. The reason is that it is not often possible to optimize for more than one variable at a time. In this situation, all of the disciplines may need to make a compromise on sub-optimal alternatives in order to close the design at all to perform the mission.

Documentation and Presentation

The basic expectation is that the team will prepare and make the midterm and final presentations. Then, they will produce a conference paper describing the overall project for the International Astronautical Congress. All well and good, but an overview paper is unlikely to convey the substantive detail that would be valuable for the permanent record. For this project, the goal will be for each of the five disciplines/subject areas to prepare their own paper for publication in the most appropriate conference or journal.

TABLE 3. Candidate Work Breakdown Structure for the Asteroid Mining Technical Project

	Research	Problem Definition	Concept Development	Concept Selection, Integration, & Refinement	Documentation and Presentation
Economics and Commercial Partnerships	Precedents of Space Enterprise, COTS, ULA and USA partnerships, Market research for rare metals	How to make a profit. Time to ROI, finance, insurance, Incorporation agreements, Deliver to market	A new kind of company or partnership? Investment strategy. Packaging, marketing, delivery	Model charter for a new company? IPO pro forma?	Midterm and Final Review Conference Paper Journal Article
International Partnerships and Treaty Obligations	Precedents of ISS, Planetary Protection, Space Treaty, Space Policy	Existing treaties & partnerships; Include the Have-nots	New treaties or amendments. Role for developing countries.	Negotiate new treaty provisions among "Model UN" of the ISU members?	Midterm and Final Review Conference Paper Journal Article
Orbital Mechanics & Trajectory Design	When you launch vs. where you go, Out of ecliptic, return opportunities	How to select launch & return windows, launch & in-space propulsion	Trajectory design using nodes or LaG. Points? Fuel depots?	Find optimal, most efficient, lowest risk, most repeatable trajectory design.	Midterm and Final Review Conference Paper Journal Article
Mission Design and Operations	Human vs. Robotic; Automation and Teleoperations; Long duration. Space Human Factors, Habitability. Extreme Environments	Define the relation between humans & machines. Human crew transit to, from & at 3554 Amun.	Concepts for crewed and uncrewed vehicles; Concept of Operations in deep space around asteroid, EVA systems.	Vehicle and Mission design. Robotics capabilities and design requirements, Crew ConOps, EVA tasks,	Midterm and Final Review Conference Paper Journal Article
Mining Technology and Operations	Earth precedents, power, cooling, drilling, extraction, material handling, refining. Extreme Environments	What to mine, where and how to process it, requirements for *mini*gravity & vacuum operations.	Concept for the mining process: prospecting, sampling, extraction, handling, refining, packaging, transport to market.	Define end-to-end mining process, including safety and risk-reduction strategy.	Midterm and Final Review Conference Paper Journal Article

References

Asaravala, Amit (2005, May 25). Astronaut wants asteroid mission, *Wired.Com,* http://www.wired.com/science/space/news/2005/05/67630, retrieved 5 SEPT 2009.

Associated Press (2007, September 27). NASA launches spacecraft on asteroid-belt mission [DAWN], http://www.usatoday.com/tech/science/space/2007-09-27-\asteroid-mission_N.htm, retrieved 5 SEPT 2009.

Campbell, John W., Ed. (1961, July). *Analog Science Fact – Fiction*. Cover art by Gene Thomas. http://www.sfcovers.net/Magazines/ASF/, retrieved 21 SEPT 2009.

Cass, Stephen (2009, August 12). Stepping Stones to Mars? *MIT Technology Review,* http://www.technologyreview.com/blog/deltav/23980/?a=f, retrieved 4 SEPT 2009.

Cohen, Marc M. (1995). Problem Definition in a Participatory Design Process, dissertation at the University of Michigan, Ann Arbor MI: Michigan Microfilms.

Cohen, Marc M. (2002 October). Design Participation in the Human Exploration Demonstration Project, AIAA 2002-6112, *1st Space Architecture Symposium (SAS 2002),* Houston, Texas, USA, 10-11 October 2002. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Cohen, Marc M. (2003). Global Overview: Returned Astrobiology Sample Mission Architectures, SAE-2003-01-2675, *33rd International Conference on Environmental Systems*, Vancouver BC, Canada, July 2003.

Couvault, Craig (2008, January 21). Moon Stuck: Space leaders work to replace lunar base with manned asteroid missions, published originally in Aviation Week and Space Technology, p. 24. http://www.spaceflightnow.com/news/n0801/18avweek/, retrieved 4 SEPT 2009.

Couvault, Craig (2009, August 17). Dual Orion capsules studied for manned asteroid mission, *SpaceFlightNow.com*, http://www.spaceflightnow.com/news/n0908/17orion/, retrieved 4 SEPT 2009.

Croley, Patrick A. (2005, December). Reachable Sets for Multiple Asteroid Sample Return Missions, Masters Thesis, Monterey, CA: Naval Postgraduate School, http://www.stormingmedia.us/23/2343/A234344.html, retrieved 5 SEPT 2009.

Damer, Bruce (2007, July 30). Design for a Human Mission to a Near Earth Object, http://www.digitalspace.com/projects/neo-mission/index.html, retrieved 4 SEPT 2009.

David, Leonard (2006, November 16). NASA Studies Manned Asteroid Mission, Space.com, http://www.space.com/news/061116_asteroid_nasa.html, retrieved 4 SEPT 2009.

Echo.JPL (2009, August 22). Delta-v for spacecraft rendezvous with all known near-Earth asteroids (q < 1.3 AU), Pasadena, CA: Jet Propulsion Lab. http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html retrieved 8 SEPT 2009.

Jones, Ross (2000). The Muses-CN Rover and Asteroid Exploration Mission, *22nd International Symposium on Space Technology and Science*, May 28-June 4, 2000, Morioka Japan, Tokyo Japan: International Symposium on Space Technology and Science.

Kawaguchi, J.; Fujiwara, A.; Sawai, S. (1996, January). Sample and return mission from asteroid Nereus via solar electric propulsion, *Acta Astronautica,* Vol 38, No. 2, pp. 87-101.

Kawaguchi, J. (2003). Hayabusa, ISAS, http://www.isas.ac.jp/e/special/2003/kawaguchi/02.shtml, retrieved 7 SEPT 2009.

Kleisius, Michael (2008, July 1). The Million Mile Mission: A small band of believers urges NASA to take its next step—onto an asteroid, Air & Space, Washington DC: Smithsonian Institution. http://www.airspacemag.com/space-exploration/Million_Mile_Mission.html?c=y&page=2, retrieved 1 SEPT 2009.

LeCompte, M. A.; Meyer, T. R.; McKay, C. P.; Durda, D. D. (2006). Near Earth Asteroid Rendezvous Missions with the Orion Crew Exploration Vehicle, Houston, TX: Lunar & Planetary Institute.

Lewis, John (1995). Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets, Helix Books.

McFadden, Lucy A.; Russell Christopher T.; Cheng, Andrew F. (1996). The Near Earth Asteroid Mission to 433 Eros, *Eos Transactions of the American Geophysical Union,* 77, pp. 73-39.

Morrison, David; Wells, William C. (1978). Asteroids: An Exploration Assessment, NASA-CP-2053. Washington, DC: National Aeronautics and Space Administration.

O'Neil, Ian (2008, May 6). NASA considers manned asteroid mission, The Guardian, http://www.universetoday.com/2008/05/06/nasa-considers-manned-asteroid-mission/, retrieved 4 SEPT 2009.

Ostro, S. J. et al (1991, June 7). Asteroid 1986 DA: Radar Evidence for a Metallic Composition, Science, Vol. 252, No. 5011, pp. 1399-1404.

Paine, Michael (2000, February 8). Space Missions: Chasing Comets and Asteroids, http://www.space.com/businesstechnology/technology/asteroid_space_missions_000211.html, retrieved 5 SEPT 2009.

Petrov, D. V.; Simonenko, V. A.; Shubin, O. N. (1996). Methods of Experimental Research of Asteroid Properties, in Johnson, Stewart, Ed., *Space Missions, Engineering, Construction, and Operations in Space V*, New York: American Society of Civil Engineers. pp. 68-73.

Sears, D.W.G., et al (2004). The Hera Near-Earth Asteroid Sample Return Mission: Science Requirements of the Sample Collector, *Advances in Space Research*, 34. pp. 2276-2280.

Sonter, Mark (2006, February 2). Asteroid Mining: Key to the Space Economy, Space.Com, http://www.space.com/adastra/060209_adastra_mining.html, retrieved 8 SEPT 2009.

Space Science Directorate (2009). Small Body Database Browser, Pasadena CA: Jet Propulsion Laboratory, http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=3554%20Amun;orb=1;cov=0;log=0;cad=0#orb retrieved 4 SEPT 20009.

Styles, Lori (2006, October 31). NASA Awards Funding For Possible UA-LED Asteroid Sample-Return Mission [OSIRIS], *Physics Astronomy Report,* http://www.innovations-report.com/html/reports/physics_astronomy/report-73051.html, retrieved 6 SEPT 2009.

Sukhanov, Alexander; Durao, Mario (2001, September-October). Low-Cost Main-Belt Asteroid Sample Return Mission, *Journal of Spacecraft and Rockets,* Vol. 38, No. 5. pp. 736-744.

Sykes, Mark V.(2006, Summer) PSI Proposes a Distant Asteroid Mission, *Planetary Science Institute Newsletter*, Vol. 6, No. 2, Tucson AZ: Planetary Science Institute.

University Of Arkansas (2000, December 25). Asteroid Sample Return Object Of Space Mission Proposed. ScienceDaily. Retrieved September 5, 2009, from http://www.sciencedaily.com- /releases/2000/12/001225061531.htm

Resume

MARC MITCHELL COHEN

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El Segundo, CA 90245

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EDUCATION

Doctor of Architecture (Arch.D)	University of Michigan, 1995	NASA Full Time Graduate Fellow
Master of Architecture (M.Arch)	Columbia University, 1977	Kinne Summer Traveling Fellow
A.B. Arch. & Urban Planning	Princeton University, 1974	Cum Laude

TEACHING EXPERIENCE

University of Southern California, Departments of Astronautical Engineering and Architecture

- Visiting Lecturer and Reviewer, Madhu Thangavelu's Space Exploration Architectures Concept Synthesis Studio, ASTE 527, and related design courses, 1992-2008.

California College of the Arts, Department of Industrial Design, San Francisco

- Visiting Design Faculty and Studio Critic for "Space Station Hygiene Facilities" Project, Susmita Mohanty, Instructor, 2005.

Rensselaer Polytechnic Institute, School of Architecture

- Member of Master of Architecture Thesis Committee for Annette Barnes, "Stairs on the Moon," 2003, Prof. Ted Krueger.

University of California, Berkeley, Department of Earth and Planetary Science

- NASA-Ames Center for Mars Exploration's Liaison to Larry Kuznetz's "To Mars by 2012" Class, Visiting Lecturer and Reviewer, 1997-2002.
  http://www.cnn.com/TECH/science/9806/04/t_t/mars.2012/ http://cmex.ihmc.us/CMEX/index.html

University of Michigan, Taubman College of Architecture and Urban Planning, 1989-1990

- Senior Teaching Assistant for Prof. Anatole Senkevitch "The History of World Architecture;" lecturer and preceptorial section leader.
- Instructor and author of curriculum for graduate course in design methodology "The Four Paradigms of Design."

California State Polytechnic University, San Luis Obispo, Department of Architecture 1987-1988

- Visiting Design Faculty, Lecturer, and Studio Critic for a Space Technology Museum Design Project, Prof. Donna Duerk.

Invited Lectures (exclusive of conference papers and faculty lectures) on Space Architecture:

- American Society for Engineering Education, Summer Study, NASA-Ames Research Center, 1992
- California State University, Fresno, 1984
- Columbia University, Grad School of Architecture, Planning and Preservation, 1984
- Keyes School, Palo Alto, CA, American Institute of Architects, Built Environment Education Program, 1987
- NASA Johnson Space Center, Space Station, Crew Systems EVA and Manned Systems Divisions, 1986
- NASA Goddard Space Flight Center, Science and Human Exploration Workshop, 2001
- NASA Marshall Space Flight Center, Space Station Common Module Project, 1987
- National Academy of Science, Lunar Bases and Space Activities of the 21st Century, 1984
- Oxford-Brookes University, School of Architecture, Oxford, UK, 1997
- Princeton University, School of Architecture and Urban Planning, Alumni Symposium, 1999
- San Jose State University, Department of Mechanical Engineering, 1985
- University of Hong Kong, Faculty of Architecture, 2005
- University of New South Wales, Lightweight Structures Division, 1996
- University of Tokyo, School of Architecture, Takahashi Studio, 1996
- University of Tokyo, School of Architecture, Matasmura Studio, 2005
- XEROX Palo Alto Research Center, 1984

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CURRENT POSITION

Human System Integration Lead, Civil Space
Advanced Programs and Technologies Division
Northrop Grumman Aerospace Systems
El Segundo, CA 90245

SUMMARY

Licensed Architect with 25+ years of experience in research and development for the Human Spaceflight Program and 5 years experience in AeroSpace and other technical facilities including wind tunnels, life science labs, simulators, and aircraft support facilities. Languages: English, French. Publications available for download from http://www.spacearchitect.org.

ACHIEVEMENTS

- LEAD for Independent Research and Development:
  - Volumetric Analysis of Crewed Spacecraft: Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume, SAE 2008-01-2366.
  - Assessment of NASA Lunar Exploration Objectives, the Space Enterprise Council Workshop, August 2006.
  - Modeling and Simulation of Crew Accommodations, Cabins, and Habitats.
- PRINCIAL INVESTIGATOR for Northrop Grumman Integrated Systems for the NASA "Exploration of the Moon and Beyond" RFI. Led a team that submitted 15 RFI responses.
- PROJECT MANAGER/PRINCIPAL INVESTIGATOR: Habot Mobile Lunar Base/Composite Habitat Project. Coordinated contributors at four NASA Centers, two DOE labs, and the University of Naples. 1 GeV/n Fe beam at Brookhaven National Lab gave proof of concept for carbon shielding.
- DESIGN TEAM LEADER: SOFIA Layout of Personnel Accommodations – on-board mission control system to put a 2.5m infrared telescope in a 747. Led multidisciplinary team of 15 professionals that developed a new approach to reduce the number of ops crew by half, double the flight rate and triple the science payload.
- PROJECT ARCHITECT: Fluid Mechanics Laboratory—Developed the $4M project for four indraft tunnels and an experimental high bay.
- INVENTOR/TEAM LEAD: Suitport EVA Access Facility—Led a team that developed the analysis for the Suitport that offers order of magnitude improvements in atmosphere loss, pumpdown time, and cooling for spacesuit airlocks. Two Suitports built into the Ames HazMat vehicle, an armored personnel carrier. US Patent No. 4,842,224.
- PROPOSAL FACILITATOR / PROJECT ARCHITECT-CONFIGURATION MANAGER for the Human Exploration Demonstration Project (HEDP). Facilitated four research divisions - Human Factors, Information Science, Life Science, and Life Support in a simulation of "A day in the life of a planetary base."

Professional Qualification: Licensed Architect, California, C15756, 1985.

Awards: 7 US Patents, 3 NASA Space Acts, 2 Ames Commercial Technology Awards, 4 NASA Tech Briefs, 3 NASA Group Achievements, American Institute of Architects Future Architecture, Industrial Designers Society Design Achievement.

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ADDENDUM: PROFESSIONAL EXPERIENCE

NASA Ames — 1979 to Present

Aerospace Engineer 5/Human System Integration Lead (1/2006-Present)
(Northrop Grumman Integrated Systems, Advanced Capabilities Development)

- Human-System Integration Lead for Altair Lunar Lander and Lunar Destination Surface Systems.
- 2008 NASA Lunar Lander Development Study proposal co-lead and contract technical team.
- Two RFI Teams: Exploration of the Moon and Beyond, Constellation Lunar Lander.
- Independent Research & Development IPT Lead for Habitability & Human Factors, Lunar Exploration.

Aerospace Engineer-Flight System Design (5/95-12/2005)
(Advanced Space Projects Branch, Systems and Project Engineering Branch)

- Led Habot (Habitat Robot) Mobile Lunar Base/Composite Habitat Project. NASA HQ Direct funding; architectural, planning engineering analysis, habitat modeling, radiation shielding testing, crew size model. (6 publications).
- Developed a $100M/10-year proposal for a design concept and glovebox/bioisolation technology for the Mars Surface Science Lab. The Mars program picked up this approach for Mars Returned Sample Handling. (4 publications).
- Co-authored, *The Reference Mission of the NASA Mars Exploration Study Team 1992-1997*. NASA SP-6107.
- Co-led team that developed the NASA Habitats and Surface Construction Technology Roadmap to guide design zero-G and partial-G habitats, and Lunar and Mars surface bases, published in NASA CP-97-206241.
- Developed the analysis and design concept for orbital or surface planetary and interplanetary habitat architectures.
- Lead 15 professionals to design the crew cabin design and on-board mission control system (Layout of Personnel Accommodations) of the 747SP for the Stratospheric Observatory for Infrared Astronomy (SOFIA). SAE 975632.

Aerospace Engineer-Manned Systems (9/83-4/95)
(Space Human Factors Office, Advanced Space Technology Office)

- Proposal Facilitator for the Human Exploration Demonstration Project, combining four research divisions to develop a proposal for $1M in-house matching funds for a simulation on the theme, "A day in the life of a planetary base." Proposal was successful and I served as Project Architect/Configuration Manager. *HEDP provided the research for my dissertation*.
- Led team that developed the analysis for the Suitport that offered improvements in atmosphere loss, pump down time, and cooling for spacesuit airlocks. US Patent No. 4,842,224.
- Developed Space Station habitability accommodations and workstations including the Space Station Wardroom Table US, Patent No. 4,836,114.
- Designed outfitting for Marshall Space Flight Center for their US Lab Module. Redrew the rack fabrication drawings for Marshall Space Flight Center and designed the Element Control Work Station with the Deployable Video Conference Table. US Patent No. 5,261,735.
- Developed and built Proximity Operations Simulator for space station. Developed space station architecture that introduced the node and cupola into the International Space Station US Patent 4,728,060.

Facilities Architect (2/79-8/83)
(Facilities Engineering Branch)

- Architect for the Fluid Mechanics Lab, combining 4 small indraft wind tunnels and basic research areas.
- Performed Aircraft Support Study of 20 aircraft and their hangar requirements and proposed a new building to collocate all the specialized U-2 support equipment and facilities. Designed the building.
- Managed 5 construction work packages in the National Full-Scale Aerodynamics Complex, the largest wind tunnel in the world.

Professional Society:
•American Institute of Aeronautics and Astronautics; Associate Fellow; Chair: AIAA Design Engineering Technical Committee; Founder of the AeroSpace Architecture Subcommittee; Session Organizer >12 International Conferences;
• International Federation of Professional and Technical Engineers (IFPTE); Founder & President at NASA-Ames for 8 years.
• National Academy of Science: Radiation Shielding Committee Member 2006-2008.