2006-527: SATELLITES, UAVS, AND GROUND-BASED WIRELESS SENSOR NETWORKS: LESSONS LEARNED FROM AN REU SITE IN ENVIRONMENTAL SENSOR DEVELOPMENT

Richard Schultz, University of North Dakota

Dr. Richard R. Schultz is associate professor and interim chair of electrical engineering at the University of North Dakota in Grand Forks. He received the B.S.E.E. degree from UND in 1990, and the M.S.E.E. and Ph.D. degrees from the University of Notre Dame in 1992 and 1995, respectively. Dr. Schultz joined the UND faculty in 1995, and his teaching and research interests are in signal and image processing, embedded systems, technology entrepreneurship, and systems engineering.

William Semke, University of North Dakota

Dr. William Semke is an assistant professor in Mechanical Engineering at the University of North Dakota in Grand Forks. He received a B.S. in Physics from Bemidji State University in 1991, an M.S. in Engineering Mechanics and Astronautics in 1993, and a Ph.D. in Mechanical Engineering in 1999 from the University of Wisconsin-Madison. Dr. Semke joined the UND faculty in 2000, where he conducts research in precision motion and vibration control, smart structures, and space hardware design, along with instruction in the areas of mechanical design and experimental methods.

Arnold Johnson, University of North Dakota

Prof. Arnold F. Johnson is an assistant professor emeritus of electrical engineering at the University of North Dakota. Prof. Johnson has been an electrical engineering faculty member at the University of North Dakota since 1988, and he served as the department chairperson from 1999 through 2005. Prof. Johnson earned his B.S.E.E. at UND in 1959 and his M.S.E.E. at Iowa State University in 1962. His teaching experience varies from numerous MBA courses to a variety of engineering courses including circuits, electronics, robotics, image processing, and senior design.

Douglas Olsen, University of North Dakota

Doug Olsen is a Project Manager for the Center for People and the Environment at UND, where he has led the student and faculty development efforts for AgCam, an imaging system to be used onboard the International Space Station, and for AEROCam, an airborne multi-spectral imaging system. He also holds adjunct faculty appointments in the Electrical Engineering and Space Studies departments. Prior to joining UND he had several engineering and management positions in the aerospace industry. Mr. Olsen has a B.S.E.E. degree from North Dakota State University (1981) and an M.S. degree in Space Studies from UND (1989).

Ofer Beeri, University of North Dakota

Ofer Beeri graduated from the University of Haifa, ISRAEL, in 2002, and he has conducted research at the University of North Dakota ever since. Dr. Beeri's focus is on the application of remote sensing in agriculture, rangeland, and wetlands. He uses evapo-transpiration estimations from satellite images to predict sugar beet yield and quality, develops remote sensing algorithms to assess rangeland productivity, and writes Geographical Information Systems (GIS) models to map water dynamics in the Missouri Cateau wetlands.

George Seielstad, University of North Dakota

Dr. George A. Seielstad is Associate Dean for Research and Innovative Projects at the John D. Odegard School of Aerospace Sciences of the University of North Dakota. In this position, he develops and promotes the Upper Midwest Aerospace Consortium (UMAC), a major research

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initiative Seielstad founded in 1994. Before coming to UND, Seielstad had an active career as a radio astronomer, first at the California Institute of Technology's Owens Valley Radio Observatory, then at the National Radio Astronomy Observatory in Green Bank, West Virginia, where he was Site Director. He earned his undergraduate degree summa cum laude from Dartmouth College. His Ph.D. in Physics is from the California Institute of Technology. Seielstad has been published widely: he has authored more than 60 refereed articles and three books, among them Cosmic Ecology: The View from the Outside In, and At the Heart of the Web: The Inevitable Genesis of Intelligent Life.

Seielstad came to UND in 1993 as Assistant Dean for Academic Affairs in the Odegard School and Professor in the Department of Space Studies. In 1994, he was named Associate Dean of the School, and Director of the Earth System Science Institute, a multi-disciplinary research organization dedicated to studying global environmental issues. In October 1997, Seielstad was named The Oliver Benediktson Professor of Astrophysics. Currently, Seielstad is Chairman of the Executive Management Board for NASA's Deep Space Network. He also served on a National Science Foundation's Committee of Visitors for the Atmospheric Sciences.

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Satellites, UAVs, and Ground-Based Wireless Sensor Networks: Lessons Learned from an REU Site in Environmental Sensor Development

Abstract

One of the one of the key goals of the National Science Foundation Research Experiences for Undergraduates program is to promote graduate education for U.S. citizens and permanent residents as they learn about the scientific research process, from developing a hypothesis, to performing experiments, to disseminating results through presentations and publications. The University of North Dakota hosted an NSF-supported REU Site with a theme of environmental sensor development during the summers of 2003, 2004, and 2005. This REU Site was a partnership between the UND School of Engineering & Mines and the Northern Great Plains Center for People & the Environment, a NASA-supported research center on the UND campus. These academic and research units have been collaborating on aerospace payload and environmental sensor development since the summer of 2000. What made this REU Site unique was that the participants worked on one large-scale environmental sensor development project during each summer as a multidisciplinary team, in addition to side independent research projects with individual faculty mentors. The primary goal was to teach the participants – mainly electrical, mechanical, and aerospace engineering undergraduate students and K-12 teachers – about systems engineering methodology, including design, build, integration, and test, with a complementary benefit of the participants practicing their communication and teamwork skills. The systems engineering projects that the participants designed during the summer months will be described, with an emphasis on lessons learned from recruiting and managing the team.

1. Introduction

The University of North Dakota hosted a Research Experiences for Undergraduates Site supported by the National Science Foundation during the summers of 2003, 2004, and 2005, with a theme of environmental sensor development. This REU Site was a partnership among the Departments of Electrical and Mechanical Engineering within the School of Engineering & Mines and the Upper Midwest Aerospace Consortium (UMAC)[10] headquartered within the Northern Great Plains Center for People & the Environment (NGP CP&E). UMAC is a research consortium focused on sustainability. It consists of eight institutions geographically distributed among the states of North Dakota, South Dakota, Montana, Wyoming, and Idaho, providing information to farmers practicing precision agriculture, ranchers seeking optimum grazing capacities, foresters engaged in sustainable forestry, educators teaching responsible stewardship, and students of Earth system science. The School of Engineering & Mines and the Upper Midwest Aerospace Consortium have been collaborating on aerospace payload and environmental sensor development at UND since the summer of 2000. The University of North Dakota is also home to the John D. Odegard School of Aerospace Sciences, which offers some of the premier aviation and aerospace educational and research programs in the world.

One unique aspect of the REU Site was that the participants worked on one large-scale systems engineering project during each summer as a team, in addition to side independent research projects with individual faculty mentors. The primary goal was to teach the electrical, mechanical, and aerospace engineering undergraduate participants about systems engineering methodology, including design, build, integration, and test, with a complementary benefit of having the participants practice their communication and teamwork skills. The three team projects carried out by the REU Site participants included the following:

- **CubeSat**. A small satellite was launched to an altitude of approximately 30-km by the 2003 REU Site participants using a weather balloon. At this altitude, extremely low temperature and pressure create a near-space environment. The undergraduates were also tasked with redesigning an existing CubeSat prototype to carry a general scientific payload constrained in mass, volume, and data transfer protocol.
- **Unmanned Aerial Vehicle (UAV)**. During the summer of 2004, the REU Site participants built a radio-controlled aircraft with a three-meter wingspan capable of lifting payloads up to four kilograms in mass. Participants also built custom scientific payloads for the UAV, including a radio-controlled net to collect mosquitoes at low altitudes and an air quality measurement instrument to capture air samples above coal burning power plant stacks.
- **Ground-Based Wireless Sensor Network for the Measurement of Evapotranspiration (ET)**. A wireless sensor network was designed, built, and tested by NSF REU Site participants during the summer of 2005, utilizing “mote” transceivers from Crossbow Technology, Inc. The system consists of portable weather stations with two levels of sensors to measure differential quantities for the estimation of evapotranspiration in a sugar beet field. ET is an indicator of sugar content, and it is of great economic value to regional farmers within the Red River Valley of the North.

The participants were also involved in two key side independent research projects throughout the three-year duration of this REU Site:

- **Agricultural Camera (AgCam)**. This payload is a two-band (red and near infrared) sensor designed for monitoring vegetation health, with ten-meter spatial resolution and better than weekly temporal resolution. It was designed primarily by electrical and mechanical engineering graduate students for installation in an Earth-observing window inside the International Space Station. REU Site participants contributed to astronaut training modules, graphical user interfaces for the flight and ground systems, and the design of custom ground test equipment.
- **Airborne Environmental Research Observational Camera (AEROCam)**. This payload is a three-band multispectral imager with one- to two-meter spatial resolution designed primarily by electrical and mechanical engineering graduate students for flight on UND Aviation fleet aircraft, with applications in precision agriculture and disaster response. REU Site participants contributed to flight testing, image mapping, and payload integration into different models of aircraft.

In the Wireless Sensor Network, AgCam, and AEROCam development projects, “citizen scientist” farmers affiliated with the Upper Midwest Aerospace Consortium assisted in defining the system-level requirements. These local farmers helped the engineering students and faculty obtain a “big picture” view of the research activities and how they fit into the context of capturing scientific data for end-users whose main goals are to lower their input costs and improve crop yields. This is certainly one of the more significant "broader impacts" of this National Science Foundation project, above and beyond intellectual merit, since it is rare that undergraduates have the chance to experience working with customers and end-users in a scientific sensor R&D effort.

Some general lessons learned from this REU Site include the following:

- Students enjoyed the team-based atmosphere, and felt that it helped improve their career and graduate school prospects.
- It takes much longer than expected for the participants to begin the construction phase of a large-scale environmental sensor development project during the summer months, so it is important for the faculty mentors to carefully scope the work up-front. This allows the participants more time to order supplies and to test their design.
- Over the span of a ten-week summer REU Site, there is usually not enough time to both design the environmental sensor and also collect reliable scientific data. Some decisions regarding engineering design versus science operations must be made by the management team before the REU Site begins.
- Ground-based and airborne sensor development projects are easier to accomplish than space-borne payloads, simply because of accessibility for debugging and maintenance. Additionally, the politics and cost of launching a payload into space generally result in long development and integration timelines, making space projects difficult to complete for undergraduates in the timeframe of a summer or even a full academic year.

This paper is organized as follows. Section 2 describes the REU Site management team and participants, as well as requirements for personnel selection. Systems engineering concepts are introduced in Section 3, with the actual projects and participant accomplishments presented in Section 4. Lessons learned with respect to REU Site recruiting, team management, project scope, schedule, and budget are outlined in Section 5, with a summary presented in Section 6.

2. REU Site Information

The University of North Dakota received a three-year National Science Foundation Research Experiences for Undergraduates (REU) Site award in May 2002:

> Project Title: "REU Site: Engaging Undergraduates in Multidisciplinary Remote Sensing and Image Analysis Research at the University of North Dakota"
> NSF Award Number: ECC-0139185
> Principal Investigator: Richard R. Schultz, Ph.D.
> Co-Principal Investigator: George A. Seielstad, Ph.D.
> Effective Dates: July 1, 2002, through May 31, 2005
> No-Cost Extension: Granted by the cognizant Program Officer through December 31, 2005.

In essence, the theme of the REU Site was "environmental sensor development," with a total of eight undergraduate student stipends and two K-12 teacher stipends provided by the NSF for three ten-week summer research experiences. Furthermore, the NSF provided academic year stipends for two undergraduate research assistants enrolled at the University of North Dakota to work ten hours per week on the project throughout its duration. The award became active too late in 2002 to recruit REU Site participants for that summer, so the management team decided to delay the start of the summer experience until 2003 with the consent of the cognizant NSF Program Officer. In addition, a no-cost extension through December 31, 2005, was granted by the NSF so that a third summer research experience could be completed in 2005.

The personnel in Table 1 served as the REU Site management team. Although not listed in the original proposal, we have had three other mentors involved, due to their expertise:

- Dr. Ofer Beeri, Assistant Professor of Earth Systems Science & Policy, Earth Systems Science Institute, Northern Great Plains Center for People & the Environment. Dr. Beeri is an expert in remote sensing for determining vegetation health.
- Mr. Bjorn F. Dahlen, Airborne Science Operations Coordinator/Research Pilot, Earth Systems Science Institute, Northern Great Plains Center for People & the Environment. Mr. Dahlen is an experienced scientific research pilot, who is responsible for the AEROCam instrument.
- Prof. Lowell P. Stanlake, Assistant Professor of Mechanical Engineering. Prof. Stanlake is an experienced radio-controlled airplane pilot and hobbyist.

These individuals did not receive any salary from the grant, but they were valuable in assisting the REU Site participants and supervising research projects.

Table 1. REU Site management team members.

Investigator	**Title(s)**	**REU Site Involvement**	**R&D Expertise**
Dr. Richard R. Schultz	Associate Professor & Interim Chair, Electrical Engineering	Principal Investigator	Digital Signal and Image Processing; Embedded Systems
Dr. George A. Seielstad	Director, Northern Great Plains Center for People & the Environment; Chair, Upper Midwest Aerospace Consortium; Director, Earth System Science Institute	Co-Principal Investigator	Earth System Science; Remote Sensing; Scientific Program Management
Prof. Arnold F. Johnson	Assistant Professor Emeritus, Electrical Engineering	Faculty Associate	Avionics Design; Project Management
Mr. Douglas R. Olsen	Project Manager, Earth Systems Science Institute, Northern Great Plains Center for People & the Environment	Senior Associate	Project Management; Satellite Integration and Test
Dr. William H. Semke	Assistant Professor of Mechanical Engineering	Faculty Associate	Mechanical Design; Vibration Analysis; Environmental Test
Dr. Chang-Hee Won	Assistant Professor of Electrical Engineering (*now at Temple University*)	Faculty Associate	Control Systems; Small Satellite Design

The management team was responsible for recruiting REU Site participants and mentoring them on various research projects. The original objective was to recruit eight undergraduate students at the sophomore- and junior-levels from the Upper Midwest Aerospace Consortium universities, with majors in engineering and science that have justifiable interests in remote sensing applications. The Upper Midwest Aerospace Consortium[10] is a nine-institution research consortium, with its headquarters and staff based in the Northern Great Plains Center for People & the Environment and chaired by the REU Site award Co-Principal Investigator, Dr. George A. Seielstad. Figure 1 shows all nine of the UMAC-affiliated institutions in the five-state region, including Sinte Gleska University, an American Indian tribal college, and the U.S. Geological Survey (USGS) Earth Resources Observation Systems (EROS) Data Center, which operates the National Satellite Land Remote Sensing Data Archive. All five states affiliated with UMAC also participate in the NSF Experimental Program to Stimulate Competitive Research (EPSCoR). The intent was to provide students in the Upper Midwest EPSCoR states with research opportunities that they could not experience at their home institutions.

Figure 1. Upper Midwest Aerospace Consortium (UMAC) partner institutions.

The original recruiting requirements are listed as follows, although they were modified each year due to program constraints and lessons learned:

1. **Eight (8) undergraduate research assistants (URAs) will be recruited from the Upper Midwest Aerospace Consortium universities**, with exceptions made in the event that all positions cannot be filled by students enrolled exclusively at UMAC-affiliated institutions. Guidelines are listed below:
   a. Eight (8) positions will be open to undergraduate students majoring in electrical engineering, mechanical engineering, aerospace engineering, agricultural engineering, computer science, space studies, physics, geography, geology, biology, chemistry, and other undergraduates enrolled in fields of study with justifiable interests in remote sensing and satellite applications.
   b. Students that will have completed their sophomore or junior years of study at the time of the summer experience will receive primary consideration.
   c. A maximum of four (4) URAs will be selected from UND applicants.
   d. A minimum of two (2) URAs will be selected from UND applicants.
   e. A minimum of two (2) URAs will be female engineering or science students.
   f. A minimum of one (1) URA will be an American Indian student, recruited from Sinte Gleska University in South Dakota or from other tribal colleges within the five-state UMAC region. American Indians have the largest minority population within the Upper Midwest, and UND is proud to offer highly-regarded American Indian programs in nursing, psychology, and medicine, as well as support to American Indian students majoring in all degree programs at the university.
   g. A single URA can satisfy more than one of these requirements (e.g., a female American Indian undergraduate who is selected to participate in the REU Site but is not enrolled at UND as a student would satisfy two requirements).
   h. URAs will not be allowed to participate in more than two (2) summer experiences at UND.

2. **Two (2) high school and/or middle school mathematics, science, or technology teachers will be recruited locally to participate in the summer program**, with recruiting assistance provided by the Dakota Science Center, a science museum based in Grand Forks, ND. Personnel at the Dakota Science Center maintain strong relationships with public school systems throughout the region.
3. **Two (2) UND participants in the summer research experience will be invited to continue their undergraduate research assistantships during the academic year**, to support continuing activities and to assist in the publication and dissemination of research results.
4. **Only U.S. citizens or permanent residents will be recruited for all positions**, per the NSF.

In recruiting for the summer of 2003, glossy flyers with prepaid postcard inquiry and application forms were designed and distributed to the eight UMAC partner universities in Idaho, Montana, North Dakota, South Dakota, and Wyoming early in the year, with a special effort made to recruit underrepresented students from Sinte Gleska University. Unfortunately, the effort was largely unsuccessful, even through a professional graphic artist working for the Earth System Science Institute designed truly awe-inspiring marketing flyers. Only one student from a UMAC-affiliated institution other than the University of North Dakota applied. We speculate that these institutions did not wish to part with their best undergraduate researchers for the summer, but why the effort was so unsuccessful remains a mystery. For this reason, the management team decided to open up recruiting to undergraduates from around the nation for the duration of the project. Recruiting challenges will be discussed in more detail within Section 5, Lessons Learned.

3. Systems Engineering for Environmental Sensor Development

The REU Site participants were involved in the design, build, integration, and test of five systems engineering projects[14]:

- CubeSat[2]
- Unmanned Aerial Vehicle[9]
- Ground-Based Wireless Sensor Network for the Measurement of Evapotranspiration
- Airborne Environmental Research Observational Camera (AEROCam)[6]
- Agricultural Camera (AgCam)[5]

The unifying architecture of these environmental sensors and vehicles is shown in Figure 2. Essentially, the entire system consists of two rather large subsystems – an environmental sensor, either ground-based, airborne, or onboard a satellite for the scientific missions described in this paper, and a telemetry and command (T&C) station, otherwise known as a ground control station. One of the key elements of introducing the participants to systems engineering is to allow them to see the “bigger picture” in order to understand the scientific mission that will take place. The most important component in Figure 2 is the scientific instrument, which measures some quantity of interest. Every other component in Figure 2 serves to either help capture the data or to transmit this information to an end-user, who can then derive information from the sensor to make better operational decisions. For example, the AgCam and AEROCam instruments involve digital imaging for remote sensing applications. The participants involved in these projects needed to appreciate that their payload or ground station simply helps capture and deliver the correct visual data to farmers and ranchers, so that they can make better decisions with respect to fertilizer application and livestock grazing. Quite often, engineering personnel get so caught up in the excitement of designing the sensor electronics, mechanical structure, and software that they lose sight of the original scientific mission. If this does occur, it is generally due to a lack of guidance and focus by the faculty mentors.

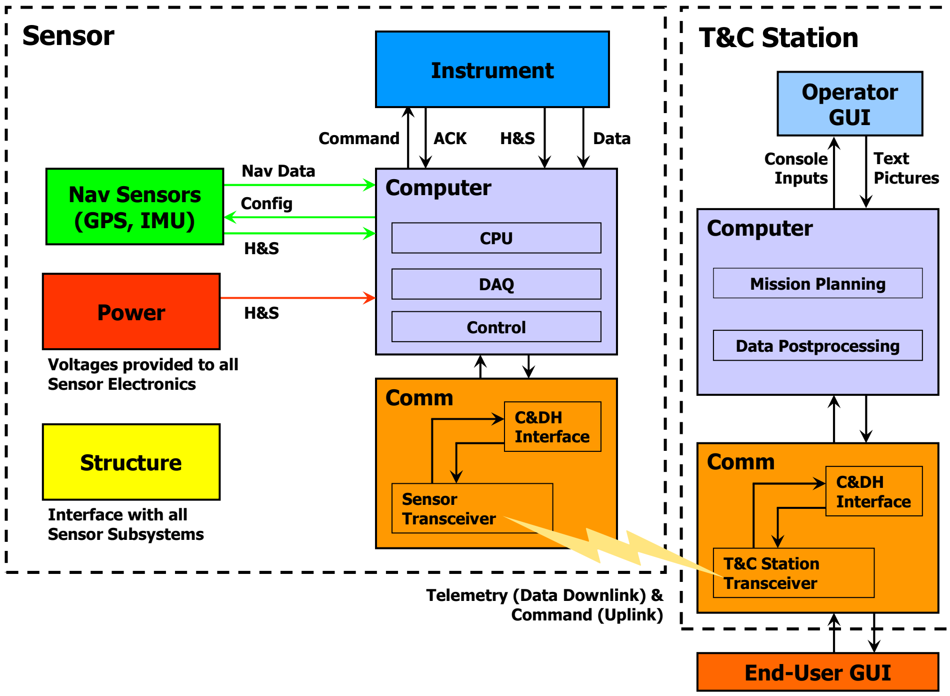

Figure 2. Environmental sensor architecture. This system diagram is appropriate for instruments that capture scientific measurements remotely and then postprocess the data within a telemetry and command (T&C) station to extract useful information for end-users. C&DH represents command and data handling, DAQ represents data acquisition, GUI represents graphical user interface, and H&S represents health and status information such as voltage, current, and temperature.

An important role of the faculty mentors is to first properly scope the sensor development project, followed by decomposing the complete system into its constituent subsystems and assigning subprojects. Once the scientific mission has been clearly defined, the majority of the needed engineering design expertise usually falls into one of three interrelated categories:

- Electrical
- Mechanical
- Software

For the REU Site, undergraduate engineering students at the sophomore and junior levels were recruited for these three primary duties, with two types of engineering students involved:

- Electrical and/or Computer Engineering
- Mechanical and/or Aerospace Engineering

Science students with interests in remote sensing were also recruited, but very few applications were received because this REU Site was perceived as an engineering research experience. K-12 teachers were involved in supporting roles, usually involving documentation and testing.

However, some K-12 teachers were highly talented, organized, and versatile individuals, who became involved in human/machine interface design with little technical background.

Figure 3 illustrates the systems engineering process that was followed by the REU Site team, which includes clearly defining the scientific mission (concept of operations), followed by sensor and T&C station design, build, test, and redesign if necessary. As expected, documentation of the projects was not performed up to the expectations of the management team, and it was rather difficult to actually make it to the point of successful operations over the span of a ten-week summer session. These lessons learned will be discussed in more detail in Section 5.

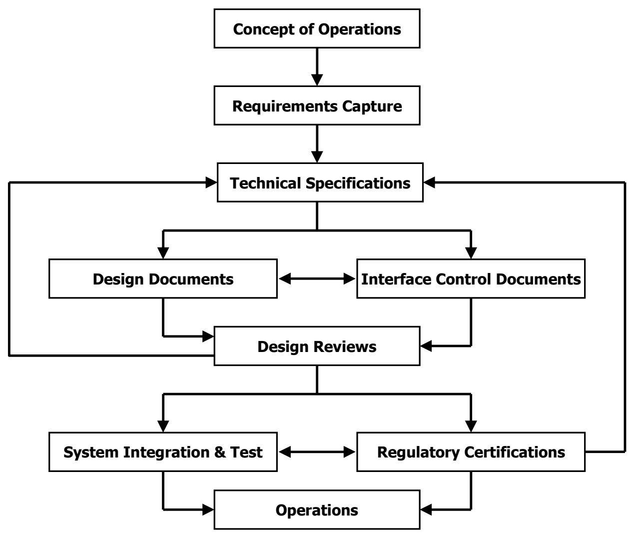

Figure 3. Systems engineering process, utilized by multidisciplinary teams for large-scale science and engineering projects.

4. REU Site Participation and Undergraduate Research Projects

Each summer of the REU Site activities will be presented, along with a listing of systems engineering project accomplishments and challenges.

Summer 2003 REU Site – Redesign of the CubeSat Picosatellite

As shown in Table 2, seven undergraduate students and one elementary school teacher participated in the REU Site during the summer of 2003, hosted by UND from May 27 through August 1, 2003. All applicants were contacted by at least one of the management team members for a telephone interview. Note that all of the undergraduate students who were selected were studying some form of engineering discipline, although we attempted to recruit undergraduates majoring in pure and applied science fields as well.

Table 2. Summer 2003 REU Site participation.

Number of Undergraduate Student Applicants and Participants	16 applicants, 7 participants
Number of K-12 Teacher Applicants and Participants	1 applicant, 1 participant
Number of Male Participants	6
Number of Female Participants	2 (1 student and 1 K-12 teacher)
Ethnicity of Participants	American Indian (1) Asian (1) White/Caucasian (6)
University Representation	California Polytechnic University (1) North Dakota State College of Science (1) South Dakota School of Mines & Technology (1) University of North Dakota (4)
Undergraduate Student Majors Represented	Aerospace Engineering (1) Electrical Engineering (3) Mechanical Engineering (2) Welding Technology (1)

As mentioned previously, recruiting for the 2003 REU Site was a real challenge. The original intent was to recruit student participants from only Upper Midwest Aerospace Consortium partner universities, to provide these institutions with an opportunity to have their undergraduate students work at the University of North Dakota over the summer months. Unfortunately, only one student from a UMAC-affiliated institution other than the University of North Dakota (i.e., the South Dakota School of Mines & Technology) applied. For this reason, the management team decided to open up recruiting to students from around the nation in March 2003, but it was too late in the spring at this point to advertise widely. Most of the national applicants discovered the REU Site on the National Science Foundation Web site.

It turned out to be very difficult to recruit two female undergraduates and one American Indian student for our first REU Site summer experience. Additionally, it became difficult to recruit two K-12 science/math teachers, since the Dakota Science Center was going through some significant organizational changes. For these reasons, we settled for hiring only one female undergraduate student (hence, a total of only seven undergraduate students) and one K-12 teacher, who also happened to be female. Although we received no interest from American Indian students up to the closing date for applications, one student did actually apply late in the spring after all of the other participants were already selected. This American Indian student was preparing to transfer to the University of North Dakota to pursue his B.S. in electrical engineering degree after completing his associate's degree in welding technology at the North Dakota State College of Science. Fortunately, this student was available and willing to participate in the REU Site.

The main systems engineering project for the summer of 2003 was the redesign of a CubeSat picosatellite[2], constrained to 1-kg in mass and 10-cm x 10-cm x 10-cm in volume. The CubeSat program was started by Professor Robert Twiggs, Director of the Stanford Space Systems Development Laboratory[8]. Prof. Twiggs developed this program to teach systems engineering principles to students through hands-on, experiential learning. University of North Dakota undergraduate engineering students started the CubeSat program prior to the arrival of the REU

Site participants. Their first design iteration, entitled ZAMBONI – Zippy Aerospace Module Broadcasting Observed Not-so-bad Images, was a double-size (i.e., 20-cm x 10-cm x 10-cm) rectangular structure that included a digital camera as a payload. The tight restrictions on the payload size made this impractical for low Earth orbit operations and image downlink to a ground station, however, and the REU Site students were tasked with redesigning the CubeSat to carry more useful scientific payloads. They converged on single cube structure designed by the mechanical engineering students on the team. The light green section of the "CubeSat To Accept Any Payload (CTAAP)" shown in Figure 4 is reserved space for a biological, material science, or electronic payload to determine its response to microgravity and radiation effects in low Earth orbit[2]. From a systems engineering education perspective, the CubeSat is almost an optimal project, since the extremely restrictive design constraints make for a challenging electrical, mechanical, and software multidisciplinary design experience.

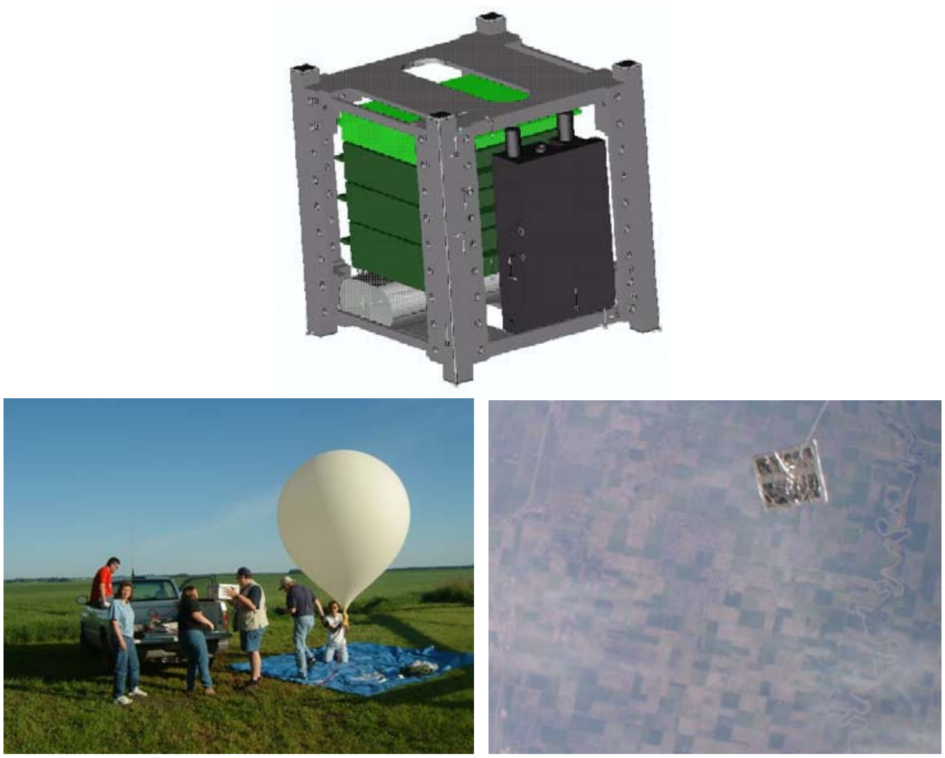

Figure 4. *Top:* CAD representation of CTAAP – CubeSat To Accept Any Payload. *Bottom Left:* CubeSat weather balloon launch on a perfect summer day in 2003! *Bottom Right:* In-flight digital picture taken at 96,400 feet, with a radar reflector suspended below the satellite. The CubeSat was recovered, intact and operational, by the REU Site participants.

Everyone helped develop the next-generation CubeSat during the summer of 2003, with the communications subsystem designed by the electrical engineers and the structure and environmental testing equipment designed by the mechanical/aerospace engineers. At first, the K-12 science teacher had no idea how she was going to fit into the team, but she soon realized that her ability to organize information was critical to documenting the R&D effort and preparing satellite technology concepts for outreach to a younger, less experienced audience.

The summer of 2003 was really a learning process for the management team on the importance of scoping a large-scale systems engineering project carefully. The CTAAP design was not built during the summer, because the participants spent about a month making the original ZAMBONI prototype function properly. The experience was considered valuable to most of the students, but the mission was not accomplished as far as the management team was concerned. Unfortunately, the CubeSat project was terminated at UND after the fall semester of 2003 because it was not possible to identify a low Earth orbit launch sponsor, and the tight restrictions on the payload size and mass make it difficult to incorporate truly useful scientific instrumentation.

Guest speakers were asked to describe career opportunities available to professionals with graduate degrees in science and engineering. The 2003 REU Site participants enjoyed discussions about their future careers, including meetings with astrophysicist Dr. George A. Seielstad, Director of the Northern Great Plains Center for People & the Environment and the Co-PI of this REU Site, and Mr. Chris McCormick, President of Broad Reach Engineering, a small high-tech business in Colorado and Arizona that specializes in space hardware development.

Summer 2004 REU Site – Development of a UAV with Scientific Payloads

The second summer of the REU Site was hosted by the University of North Dakota from June 2 through August 13, 2004. Recruiting for the summer of 2004 was conducted quite differently. First, the REU Site management team decided to open recruiting up nationwide for the second summer of the research experience, in order to attract more non-University of North Dakota applicants. A marketing flyer was designed by the Principal Investigator that could be conveniently distributed via e-mail, and it was sent out to the other REU Site Principal Investigators and administrators in early February 2004. As a result, the number of applicants from outside North Dakota rose dramatically. Because of the larger number of applicants, a two-stage telephone interview process was conducted with all of the applicants. Each management team member was asked to call a small number of applicants during the first screening phase. Each applicant recommended for a second screening then participated in a conference call with all available management team members, in order to determine the applicant’s true interest in environmental sensor development and scientific instrumentation. Table 3 shows the demographics of the 2004 REU Site. Since no American Indian students applied, only seven undergraduate students were invited to participate.

Table 3. Summer 2004 REU Site participation.

Number of Undergraduate Student Applicants and Participants	36 applicants, 7 participants
Number of K-12 Teacher Applicants and Participants	2 applicants, 2 participants
Number of Male Participants	6 (5 students and 1 K-12 teacher)
Number of Female Participants	3 (2 students and 1 K-12 teacher)
Ethnicity of Participants	Indian (not American Indian) (2) White/Caucasian (7)
University Representation	Illinois Institute of Technology (1) New Jersey Institute of Technology (1) Rose-Hulman Institute of Technology (1) Rutgers University (1) University of Central Florida (1) University of North Dakota (2)
Undergraduate Student Majors Represented	Aerospace Engineering (1) Aerospace & Mechanical Engineering (1) Computer Engineering (1) Electrical Engineering (2) Mechanical Engineering (2)

This year's REU Site revolved around the development of an Unmanned Aerial Vehicle (UAV)[9], shown in Figure 5. The need for the School of Engineering & Mines to own a launch vehicle for environmental sensor development, along with growing research opportunities in homeland security and airborne surveillance, drove the decision to build a UAV platform. The seven students and two high school teachers involved in the REU Site gained valuable experience in defense-oriented R&D, while the faculty supervisors started moving their research activities in the direction of new federal funding opportunities.

After spending the first week studying UAV platforms and their applications, the participants decided on buying a large model airplane kit rather than designing their own. In essence, a quarter-scale, single-engine, radio-controlled airplane kit was purchased and built by the participants. This large plane has a wingspan of approximately three meters, and the students determined empirically that it can lift scientific instrument payloads up to four kilograms in mass. All of the REU Site participants enjoyed working on this project – with the variety of tasks available, there was something for every undergraduate engineering discipline represented on the team as well as for the two K-12 teachers. Luckily, one of the mechanical engineering students was also an accomplished R/C airplane pilot, and he was responsible for flying the plane.

Figure 5. *Upper Left:* Albatross Unmanned Aerial Vehicle in flight (3-meter wingspan, capable of carrying payloads in excess of 4-kg). *Upper Right:* Albatross UAV with the BugHunter payload installed, used for controlled mosquito catching above the ground. *Bottom:* 2004 NSF REU Site participants next to the R/C airplane during its construction.

The UAV was built with a bay designed to accommodate small rectangular payloads. Although time was quite limited because the airplane took much longer to build than anticipated (approximately six weeks), the REU Site participants also designed, integrated, and flew several payloads using the UAV:

1. **Digital Camera** – A commercial-off-the-shelf digital camera with custom electronics installed for controlling the shutter. The camera pictures were examined on the ground after the UAV's mission was complete.
2. **BugHunter** – A payload used for collecting mosquitoes above the ground. One of the scientists affiliated with the UND Earth Systems Science Institute is a specialist in mosquito-transmitted diseases such as the West Nile virus, and he wanted the students to develop a payload capable of capturing insects at various heights since virtually all previous mosquito studies have been conducted at ground level.
3. **Coal-Fired Power Plant Stack Sampler** – The Energy & Environmental Research Center (EERC) is a world-renowned research unit on the University of North Dakota campus, supported in part by the Department of Energy. One of their key areas of expertise is the development of clean coal combustion technology, so they are very concerned about the emissions from coal-fired power plants. An EERC engineer designed and built a self-contained, self-powered, cylindrical drum tape sampler for the

UAV payload bay capable of capturing particulate matter, and it was flown by the REU Site participants on the last day of the summer research experience.

Guest speakers were invited to discuss their careers in science and engineering with the REU Site participants. Local speakers from the University of North Dakota included Dr. Rodney S. Hanley, a biologist with the Earth Systems Science Institute who specializes in the biogeography of invasive species, and Dr. Matthew L. Nilles, a microbiologist who conducts research on bacterial pathogens within the UND School of Medicine & Health Sciences. Specifically, Dr. Hanley discussed his interest in the BugHunter payload and why he needs mosquito population samples for his research on biogeography, and Dr. Nilles introduced the participants to potential biological pathogens that could use an airborne detector flown as a UAV payload to protect against bioterrorism. Two NASA experts were also brought to campus to meet the students. Dr. Adam Steltzner, Flight Systems Chief Engineer with the Jet Propulsion Laboratory in Pasadena, California, talked about his experiences in helping to design and build JPL's twin rovers, Spirit and Opportunity. Dr. Steltzner discussed the rovers' development, testing, and recent trip to the Red Planet. In the "Marsapalooza" tour sponsored by JPL in 2004, he talked to over 10,000 K-12 students, and his presentation about the rovers and careers in science was very inspiring. Additionally, Dr. Steltzner delivered a public talk entitled "The Mars Rover – Today and Tomorrow" during his stay in Grand Forks. Finally, Dr. Steve Dunagan, a UAV applications specialist and payload developer with the Ecosystems Science & Technology Branch at NASA Ames Research Center, spoke to the REU Site participants about UAV scientific mission design for civilian operations. The students had a chance to ask pertinent questions about their UAV and the payloads they were developing from a leading expert in the field.

Once again, the scope of the project was too large for a ten-week undergraduate project. It was expected that the R/C airplane would be flying by the Fourth of July, with the rest of the time spent designing and operating scientific payloads. All system testing took place during the last two weeks of the summer experience. For the most part, the summer was successful, except that no meaningful scientific data was gathered in 2004.

Summer 2005 REU Site – Ground-Based Wireless Sensor Network for the Measurement of Evapotranspiration

Table 4 shows the demographics of the 2005 REU Site, hosted on the University of North Dakota campus from June 1 through August 9, 2005. Recruiting was conducted in a similar manner as the previous year, but more University of North Dakota students were selected once again.

Table 4. Summer 2005 REU Site participation.

Number of Undergraduate Student Applicants and Participants	38 applicants, 6 participants
Number of K-12 Teacher Applicants and Participants	2 applicants, 2 participants
Number of Male Participants	7 (5 students and 2 K-12 teachers)
Number of Female Participants	1
Ethnicity of Participants	White/Caucasian (7)
University Representation	North Carolina State University (1) Purdue University (1) University of North Dakota (4)
Undergraduate Student Majors Represented	Aerospace Engineering (1) Electrical Engineering (3) Electrical Engineering Technology (1) Mechanical Engineering (1)

No American Indian students applied to participate, and one female undergraduate student who accepted a position declined to participate the week before the REU Site was set to begin. At that point, it was not possible to replace her. This is why only six undergraduate students were involved in the 2005 REU Site.

The 2005 REU Site project involved the development of a ground-based wireless sensor network to measure evapotranspiration (ET), a predictor of vegetation health in regional crops[3]. ET is modeled from climate information collected by weather stations, including net radiation, wind speed, air temperature, and humidity, to estimate the potential ET for the 15-25 miles around the station[11]. Calculation of the actual ET for a specific location, such as an agricultural field, requires the installation of a weather station inside the field. For a higher-resolution estimation of ET, satellite-driven models have been developed. One of the most promising models is the Surface Energy Balance Algorithm for Land (SEBAL) that combines satellite images and weather data from network stations[1]. One advantage of this method is its large coverage, while another is the ability of satellite images to represent the spatial variability of albedo and canopy roughness that affect ET calculations. SEBAL is a physical model, in which Earth system processes integrate to estimate ET on a pixel-by-pixel level. This model requires data from three different spectral regions (i.e., visible, near infrared, and thermal infrared) and three climate parameters from regional and/or national weather station networks (i.e., water vapor and wind speed). Information from the visible and near infrared satellite bands is used to estimate surface roughness and emissivity via vegetation indices, such as the normalized difference vegetation index (NDVI). The visible and near infrared satellite bands are used to calculate surface albedo. The last spectral region, the thermal infrared band, is used together with the emissivity and water vapor content to calculate surface temperature. These data are incorporated with wind speed to calculate the energy budget components and to estimate the actual ET for every pixel in the image. Only the combination of satellite data capturing three different spectra regions and a ground-based weather station network can account for all the required physical units and processes.

The project was well-scoped by the management team before the start of the REU Site, with "mote" transceivers[4] ordered from Crossbow Technology, Inc., ahead of time so that the participants would have as much time as possible during the ten-week session to design the sensor stations and deploy their network in the field. The portable weather station shown in Figure 6 captures similar measurements at two levels to estimate the moisture transpiration rate of the sugar beet plants into the atmosphere[13].

Figure 6. *Left:* CAD representation of the wireless sensor weather station. *Right:* Undergraduate engineering student weather station designers in a local sugar beet field. From this figure, you are able to get a sense of the height of the sugar beet leaf canopy later in the growing season. The lower anemometer indicated a much lower wind speed near the canopy than the upper-level anemometer, which gave the REU Site participants an intuitive understanding of why the differential measurements were needed.

Figure 7 shows the sugar beet field at the beginning of the growing season, prior to the leaf canopy appearing above the surface of the soil. All five ET stations designed, built, and tested by the REU Site participants are capable of capturing sample values and transmitting their data wirelessly. The center station also contains a wireless transceiver from MaxStream, Inc.[7], which communicates to a second MaxStream transceiver at a nearby farmstead. This particular wireless transceiver can transmit over 30 km if a clear line of sight is available between antennas. For this purpose, the antenna was placed at the highest point on the tower. The four other stations were positioned around the relay station, with motes used to deliver temperature, wind speed, humidity, and solar radiation sensor values to the relay station. In essence, motes are miniature battery-powered wireless transceivers with the ability to send sample values to either a central location or to one another. The Crossbow Technology data sheets[4] claim that the motes used in this project are capable of communicating over 200 meters; however, the participants soon discovered that data sheets can be quite misleading, as they found that the motes could only transmit over a range of about 100 meters for their scientific application because of the signal loss due to the leaf canopy and moisture rising from the plants. For this reason, it was necessary to place each of the four ET stations less than 120 meters from the relay station.

Figure 7. *Left:* Sugar beet field at the beginning of the growing season. *Right:* Wireless ET sensor station placement in a sugar beet field. The center ET station is capable of relaying data to a farmstead-based Web server through a long-range (i.e., 30 km) line-of-sight transceiver, while the other four ET stations are only equipped with motes for short-range (i.e., 100 m) communications.

The REU Site participants had the chance to learn that theory, simulations, laboratory work, and field tests all have their own unique challenges and provide opportunities to learn new concepts. In this case, the sensor and mote data sheets provided technical specifications that were difficult to verify in the laboratory, and these components were even more off-spec in the field. Ensuring that the electronics can operate on battery power for extended periods of time was another real-world challenge that the students faced. Ensuring that the electronic components and batteries were weather-proof made the participants take into account extremes in temperature as well as rain, moisture, and lightning, which makes the design process even more challenging for custom sensors that must operate reliably in the field over long periods of time.

During the 2005 REU Site, Mr. Gary Wagner, a local sugar beet farmer and "citizen scientist," held an open discussion with the group. He spoke about the types of scientific data that farmers require to make more informed decisions. He also mentioned how the weather stations must be designed to fold down during fertilizer application, and that these sensor stations could be highly susceptible to lightning since they will most likely be the tallest structures in the field. Mr. Wagner talked about how the cost of such weather stations would be a critical decision-maker for purchasing by regional farmers, and how one of his most important needs – monitoring the amount of rainfall in each one of his fields – was not measured by these stations. The participants became aware of the importance of speaking with end-users and capturing system-level requirements at the early stage of R&D, which is often not practiced by engineering students during their education. Mr. Wagner allowed access to his land and farmstead office for the evapotranspiration field studies. Dr. Jon Christopherson and colleagues from EROS Data Center in Sioux Falls, South Dakota, also spoke to the REU Site participants on their airborne test range, sensor technologies, geospatial engineering, and photogrammetry. EROS Data Center facilities were utilized to help calibrate the AgCam sensor during the summer of 2005.

Independent Research Projects

The REU Site participants were also involved in two key side independent research projects throughout the three-year duration of this REU Site, namely the Airborne Environmental Research Observational Camera (AEROCam), shown in Figure 8, and the Agricultural Camera (AgCam), depicted in Figure 9.

The AEROCam mission[6] is to capture multispectral images for precision farming, ranching, and forestry applications in the Upper Midwest, with requested image maps delivered to end-users via the Internet after postprocessing (i.e., georectification, mosaicking, pseudocolor generation, and normalized difference vegetation index map generation). Although the three bands currently used include red, green, and near infrared, blue and thermal infrared bands would also be useful in the future. On the AEROCam sensor, REU Site participants contributed to flight testing, image mapping, and payload integration into different aircraft models of aircraft.

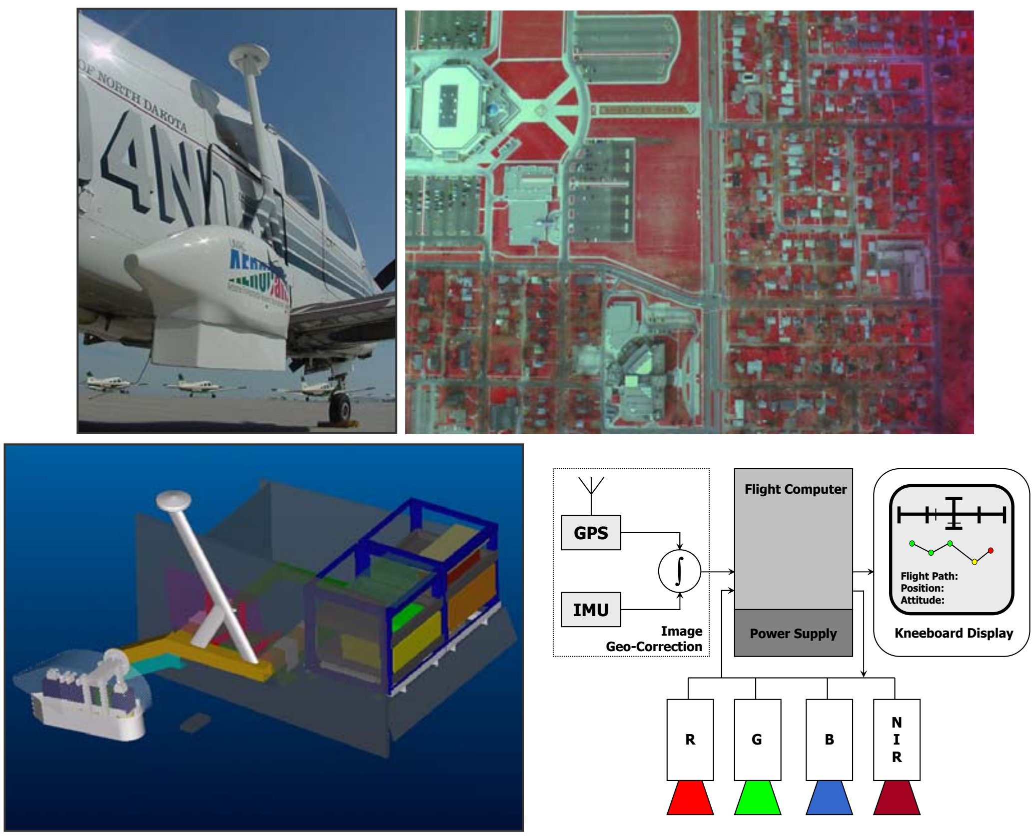

Figure 8. *Upper Left:* AEROCam multispectral camera installed in a UND Aviation single-engine airplane. *Upper Right:* AEROCam-captured image of the UND campus, with red, green, and near infrared bands shown in pseudocolor. *Lower Left:* CAD representation of the payload structure installed in the airplane luggage bay, with camera pod, GPS antenna, and computer/avionics racks highlighted. *Lower Right:* General AEROCam system block diagram.

The AgCam mission[5] is to capture two-band (red and near infrared) images for precision farming, ranching, and forestry applications in the Upper Midwest from an Earth-observing window in the NASA International Space Station, with requested image maps delivered to end-users via the Internet after postprocessing. On the AgCam sensor, REU Site participants contributed to astronaut training modules, graphical user interfaces for the flight and ground systems, and the design of custom ground test equipment.

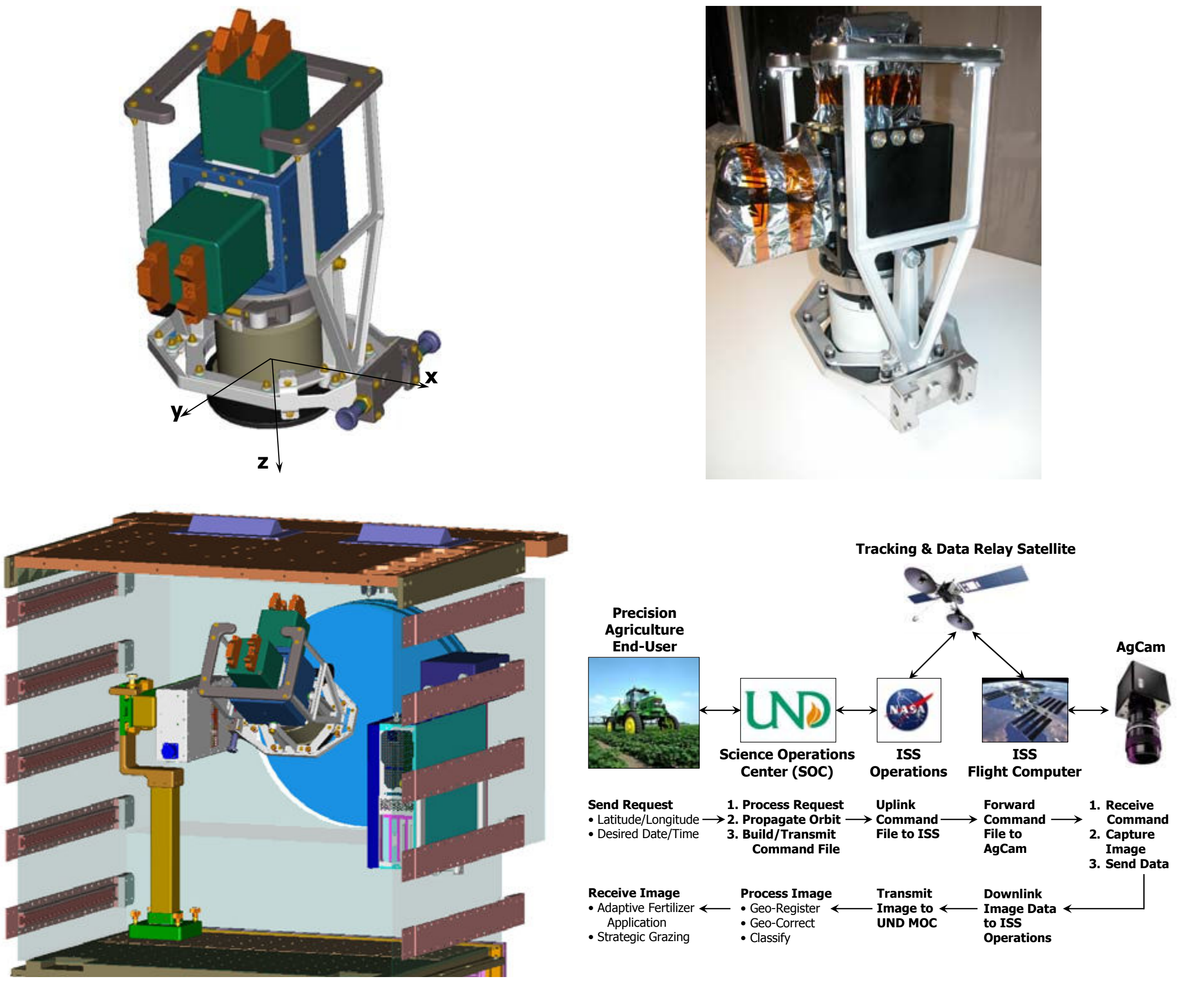

Figure 9. *Upper Left:* CAD representation of the two-band AgCam imager. *Upper Right:* AgCam flight model. *Lower Left:* CAD representation of AgCam inside the Window Observational Research Facility (WORF) onboard the NASA International Space Station. *Lower Right:* Block diagram of AgCam mission operations.

A number of the 2003 REU Site participants became deeply involved in the AgCam project. As a professional-quality instrument development effort that requires NASA payload integration into the International Space Station, graduate-level expertise is required to design, build, and test the imager. In this case, the REU Site participants served as their assistants, becoming involved in designing graphical user interfaces for the astronauts, developing astronaut training protocols, and designing ground support equipment for testing the cameras and other hardware. On the second day of the 2003 REU Site activities, a NASA conference call was scheduled with the astronaut training team! All of the participants seemed to enjoy talking to NASA professionals during numerous conference calls and design reviews. Our K-12 teacher helped design a training curriculum to instruct astronauts on the installation and operation of the AgCam sensor before their shuttle flight to the International Space Station.

Several of the 2004 REU Site undergraduate students were involved in the AEROCam project, specifically in tuning algorithms related to inertial navigation system (INS) and global positioning system (GPS) integration. They also designed a new structural mount for the imager so that it can be installed inside the bulkhead of a twin-engine aircraft rather than outside the baggage compartment of a single-engine Piper Arrow. This allows for easier FAA certification and transport of the imager from site to site. Two of the undergraduates were involved in building a training model of the AgCam payload, required by NASA for the hands-on training of astronauts in payload installation procedures at Johnson Space Center. Other independent research projects related to unmanned ground vehicles, sensor and actuator design, autopilot waypoint navigation, and embedded systems development were initiated by the faculty mentors.

During the summer of 2005, a number of the REU Site participants became involved in the AgCam project, particularly in ground station software verification and camera calibration. A couple of the undergraduates also became involved in the ongoing development of a fuel cell-powered vehicle that was being prepared for a cross-country race during the latter part of the summer. Of note – our two K-12 teachers, both educated in the humanities, were asked to help design the graphical user interface screens used by AgCam ground control station operators. With no prior knowledge of Visual BASIC or engineering design, they constructed a very elegant user interface using this software tool. The lesson learned here is that all personnel have value, and they just need to be challenged outside of their training and comfort zone.

5. Lessons Learned

From our experience over the last three years, we have compiled a number of "lessons learned," which are tailored to REU Site management teams. First, we will examine a number of expected REU Site outcomes in Table 5, to see whether or not the project had a great benefit to the participants and the management team members. These expected outcomes have been identified by the management team as a way to measure the success of the REU Site, as well as the level of professional development experienced by both the participants and the management team.

Table 5. REU Site expected outcomes and estimated level of success.

Expected Outcome	Estimated Level of Success
Large number of peer-reviewed publications	Low – It became very difficult to have the REU Site participants contribute to peer-reviewed publications during their involvement with the program.
Increased level of future federal grant opportunities	Medium – The REU Site projects provided experience in working with student teams, as well as allowing the management team members to explore a variety of sensor development projects and focus their future efforts.
Workforce development of the REU Site participants	High – The participants received an excellent education in engineering design, communications, and teamwork, and they were exposed to many hands-on technical concepts that they could not observe in the classroom.
Large number of undergraduate participants entering graduate school	Low – Recruiting undergraduate engineering students who are U.S. citizens or permanent residents is very challenging because of the many opportunities that they face when they receive their B.S. degrees. Of the 20 undergraduate student participants to date, only three of the students have started graduate school at the Master's level. Of those three, only one has attended the University of North Dakota.
Increased diversity within science & technology fields	Medium – This particular REU Site was relatively successful recruiting women (4 students, 2 K-12 teachers), but we had a very difficult time recruiting American Indians (1 student), the predominant underrepresented population in S&T fields within the Upper Midwest.

As one can tell, the results are truly mixed. The most important outcome to the management team is recruiting excellent graduate research assistants into our research laboratories, and from this perspective, the project was not successful. However, if professional and workforce development of both the students and the faculty mentors are taken into account, the REU Site experience was indeed a great success.

One issue that must be addressed is how to recruit engineering students who are U.S. citizens or permanent residents into graduate school. From the experience of the management team, this is very challenging, even when the students are exposed to state-of-the-art, exciting research projects as undergraduates. This issue will become more and more critical over the coming decades. U.S. citizens should be granted incentives by the federal government to enter graduate school – including free tuition and attractive graduate assistantships/fellowships – so that we can train our next generation of university faculty, corporate laboratory directors, and federal government program managers and policy makers.

Next, lessons learned by the management team will be listed by category, including the uniqueness of the REU Site, recruiting and personnel, K-12 teacher participation, salary and housing, project scope, and accomplishments and disappointments.

Uniqueness of REU Site

In exit interviews, most of the participants admit that they genuinely liked working together as a part of a multidisciplinary team on a large-scale systems engineering project. Several of the undergraduates who had participated in REU Sites at other universities prior to their stay at UND mentioned that these research activities were rather lonely experiences, and they commented that the social interaction provided by multidisciplinary teamwork made the experience both more fun and productive. To be fair, several undergraduate students mentioned in private that they did not like the team experience, but this had to do more with group dynamics and the inevitable personality conflicts that arise in large-scale projects.

A team leader from the group of participants was not appointed, although this is the logical step for the management team to take. Rather, we allowed a team leader or leaders to “bubble up” based on personality, desire, and experience. Prior to the REU Site, the management team tried to appoint student team leaders based on their academic abilities, and this generally did not work. Management skills are often innate, especially for inexperienced students who are used to working by themselves on projects. Allowing the “best” leaders to reveal their traits to the team seemed to be an appropriate path.

It was challenging for many participants to divide their time on a primary group project and a secondary independent research effort. Because of this, participants were not required to work on independent projects, especially if they felt overwhelmed by the group systems engineering design project. In the future, the management team would most likely have the participants dedicate themselves to the environmental sensor development R&D effort, in order to have more time for field testing and operations.

For the simple reason that the REU Site participants work as a team, group dynamics come into play in managing this type of project. For the most part, the participants worked well together. As expected, some of the less talented undergraduate students were not accepted by the group. Additionally, some of the most talented and egocentric undergraduates either chose to work independently or were forced to work outside the group. This was the first time most of the participants had experienced the true effects of group dynamics, because they had never worked on a large project before that required more than two or three personnel. It should be mentioned that in all cases, the K-12 teachers fit in well with the undergraduate students and were accepted by the group.

Recruiting & Personnel

Recruiting is the most challenging aspect of any group project, and always the most important. In some ways, each REU Site has been a startup venture, in which objectives must be reached within an incredibly short span of ten weeks. This constraint means that a self-motivated team must be recruited, and it truly limits what can be accomplished. In essence, the REU Site participants are provided with a small business experience in which everyone is given a large amount of responsibility because each person affects the bottom line.

Recruiting undergraduate researchers from the Upper Midwest Aerospace Consortium-affiliated institutions turned out to be much more difficult than anticipated. The management team anticipated that the science and engineering students enrolled at the UMAC universities would jump at the chance to work on environmental sensor R&D projects at the University of North Dakota, but recruiting these students was not been successful. Having the REU Site open to all eligible undergraduate students from around the nation has actually been more effective.

Pure and applied science (i.e., chemistry, physics, biology, and geography) undergraduates have not applied to participate in our REU Site. Engineering students of all disciplines have been the most interested in our program, and this has driven the types of projects that can be accomplished. Recruiting for specific technical skill sets was also tried, but it was unsuccessful. Rather, the management team recruited undergraduate students based on their engineering majors, seeking out the most qualified people in each discipline for the projects.

Recruiting American Indian undergraduates is also extremely challenging. The American Indian culture is tied very closely to the extended family. Primarily because of child care and transportation concerns, it is generally difficult to host American Indian students far from their homes. It has been discovered through conversations with tribal college administrators that American Indian students prefer to stay on their reservations and work at their local tribal colleges over the summer months, if given the opportunity to pursue undergraduate research. It would be advantageous to bring the research projects to the tribal colleges and high schools, in order to build a relationship with this underrepresented population.

In future REU Sites, women, American Indians, and first-generation college students would most likely be the underrepresented populations in science and technology targeted by the University of North Dakota.

K-12 Teacher Participation

K-12 teachers involved in the REU Site have truly enjoyed the experience, although they are generally intimidated at first by the skills of the engineering undergraduate students. In fact, one of our elementary school teachers said that she expected the engineering students to treat her differently because of her level of experience, but she was pleasantly surprised to discover how well she contributed to the team. Many of her perceptions of engineering students were quickly erased as she worked with a number of highly creative, extraverted individuals.

Recruiting K-12 science teachers has been very difficult. Fortunately, our REU Site has been able to hire excellent teachers from among very few applicants. Out of the five K-12 teachers who have participated in our site, every teacher possessed excellent organizational skills, which helped them contribute a great deal to the group and independent research projects. All of the teachers worked on documentation, helping the engineering undergraduates with their writing and presentation skills. The teachers were all willing to learn and take on new challenges, such as the development of graphical user interfaces, software verification, building the unmanned aerial vehicle, and troubleshooting. The goal of having the K-12 teachers take some of this experience back to their classrooms to entice their own students into science and technology careers has not been quantified, but it is most likely taking place.

Salary & Housing

The taxable gross salary of $4,500 for ten weeks over the summer months was acceptable to the engineering undergraduate and K-12 teacher participants. However, engineering students are often able to make over $700 gross salary per week in cooperative education positions over the summer time. Thus, to be competitive, the REU Site stipend should be increased, especially for engineering students who have the chance to interview for cooperative education positions as well as undergraduate research opportunities. The academic year salary of $10/hour for the two undergraduate research assistants to work ten hours per week during the school year was more than acceptable.

Many out-of-state participants lived in university housing during the summer months. During exit interviews, one common theme from out-of-state students was that it would have been much easier for the REU Site to simply pay for university housing ahead of time, and then pay the stipend balance as salary over the summer months. Although this was not an option at the University of North Dakota due to administrative constraints, some campuses may be able to work with their housing offices to use National Science Foundation funds to directly pay for the participants' housing expenses at the beginning of the summer, or to provide the housing allowance up-front if the participants choose to find their own apartments.

Project Scope

Probably the most important lessons learned came from scoping the ten-week summer project. The management team truly learned by trial and error in this regard. The original intent was to have the REU Site participants involved in a large-scale systems engineering group project every summer, similar to the AEROCam, AgCam, and CubeSat projects already being worked on by University of North Dakota undergraduate and graduate engineering students. However, ten weeks is a very short amount of time for a new team to just understand the scientific mission, let alone learn new engineering concepts to build a complete sensor system. It was very important for the management team to decide on a particular scientific mission and environmental sensor development project before the REU Site participants arrived, so that they could begin the steep learning curve immediately.

During the first summer, the management team decided that the REU Site participants would work on redesigning a CubeSat, but no particular scientific mission was defined. Frankly, this was a huge error in judgment on the part of the management team. The participants floundered for about four weeks, resulting in a summer experience with few quantifiable outcomes other than a weather balloon launch of the previous prototype. After this experience, the management team members made sure that the 2004 REU Site participants started working on the UAV project from day one, with scientific missions surrounding the development of payloads. Although the REU Site participants selected and ordered an R/C airplane kit during the first week, it still took them about five weeks to construct the plane before they could fly it for the first time. This second summer resulted in a better project scope and outcomes that were more favorable to the management team, but they still felt that the participants could accomplish more given a well-defined project that could actually be finished in a ten-week period. This resulted in the ground-based environmental wireless sensor network during the summer of 2005. A very specific scientific mission of measuring evapotranspiration in sugar beet fields was given to the participants on the first day of the site. This project was scoped ahead of time, with the Crossbow Technology, Inc., motes on order before the participants arrived on campus. In this case, a single ET sensor station was up and running after only five weeks, but this was still not enough time for the participants to conduct ample field testing to capture good scientific data.

On a related topic, working with vendors to purchase components and supplies can take a significant amount of time, with delivery dates often weeks later than when an order is placed. From day one of the REU Site, it is critical for the participants to understand that purchasing supplies can take time, and that their trade studies for various components should include the delivery date. In addition, all components were placed on overnight or two-day delivery, even though this shipping cost was excessive. Speed is of the essence when there are only ten weeks available to finish a large group project.

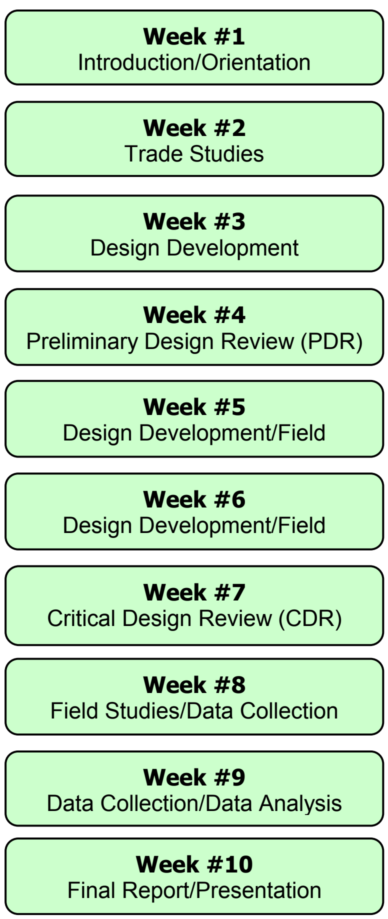

Figure 10. REU Site summer program schedule.

To keep the large-scale project on schedule, is was important for the entire team to meet regularly to discuss progress and issues that arose. At first, the team met on a daily basis, but this served to impede progress more than it actually helped the project move forward. Eventually, we converged on two full team meetings per week during the summer – one on Monday morning and one on Thursday morning – with additional weekly meetings held with only subsets of the team working on particular subsystems. Even though the participants were working together in the laboratory most of the time from Monday through Friday, these large and small group meetings were still essential for everyone to be informed and to resolve issues.

From these three summer REU Sites, the program schedule and milestones shown in Figure 10 was developed by the management team. Given all the time constraints placed on the REU Site participants, especially their significant learning curve and the need for extensive field testing of the sensors, this schedule should have the highest probability for success in the development of a working sensor system. In this case, success means not only designing, building, and testing the sensor, but also capturing useful scientific data from the field in a span of ten weeks. If the local students can stay on campus to work until the school year begins (probably about two additional weeks), then more field testing could be accomplished. Two of the major milestones include the Preliminary Design Review (PDR), essentially a management review of a paper design of the system and any laboratory/field experiments conducted to date, and the Critical Design Review (CDR), a more thorough review of the participants' design choices and prototype subsystems by the management team.

An important point to note is that the National Science Foundation typically does not provide funds for REU Site equipment and supplies. It is critically important that the management team requests nonmandatory institutional matching funds for an REU Site that develops a system outside the scope of ongoing graduate-level research at the university. Our management team was able to secure about $15,000 per year from the Offices of the Vice President for Research and Vice President for Academic Affairs & Provost, to supplement the $100,000 per year received from the National Science Foundation. Without these equipment and supply funds, this type of team-oriented summer experience would not have been possible.

Accomplishments & Disappointments

With a new team forming every summer, the REU Site participants actually accomplished a great deal. They designed and built working electronic and mechanical systems in a span of ten weeks, which is no small feat. The largest success of this particular REU Site was the workforce development aspect. Undergraduates were exposed to a "real-world" research and development experience, complete with design decisions, budgetary and schedule constraints, and group dynamics among the team members. Most certainly, they will be ready to contribute to a corporate engineering design team when they graduate and enter the workforce.

All of the REU Site participants learned that creativity and innovation are the keys to technology development, which can make engineering and science careers challenging and even fun. This is an important outcome, particularly with the image that engineers and scientists have in today's society. If this fun aspect of engineering and science careers can be brought down to the middle school level, it may be possible to attract more qualified people into technological careers.

Without a clear scientific mission and project objectives, the REU Site participants could not build a working sensor system in a span of ten weeks. Although the management team became more focused each summer on the scientific mission, this is critical to keep the participants on task. Unlike conventional REU Sites in which the students work one-on-one with a faculty member, contributing to a small, ongoing research project, the participants involved in a group project must complete their work by the end of the summer. Similar in nature to a product development experience, a focus on schedule, performance, and budget is the key to success in this type of environment.

Of course, expectations by the management team are always too high at the beginning of the summer research experience, as is the learning curve for the participants. Maybe the biggest disappointment from the perspective of the management team members is that the students were not involved in the authorship of many publications based on this work. Getting the undergraduate students to even document their research was challenging – getting them to commit to writing a research paper (even with excellent examples provided at the beginning of the summer) turned out to be virtually impossible. With a more conventional REU Site experience (i.e., more one-on-one research), it would be much easier to involve the participants in preparing publications and presentations.

The other major disappointment is that the University of North Dakota undergraduate engineering students hired to continue the research during the academic year on an hourly basis failed to accomplish much. The students were employed for up to ten hours per week, but they became so inundated with their courses and laboratory work that the research did not take a priority in their lives. This was certainly not anticipated when the original project was conceived, but it is a reality of life for the modern college student – the best undergraduates become over-involved in trying to maintain the highest grades, in leading student organizations, and even in keeping part-time jobs both on and off campus. Expectations for the academic year hourly research need to be kept very low, unless a truly highly self-motivated student who takes direction well can be recruited.

To end on a positive note – the workforce development aspects of this project did receive accolades from the corporate world. One 2004 REU Site undergraduate from the Rose-Hulman Institute of Technology wrote an e-mail back to UND in late 2004, in which she mentions how beneficial her summer research experience turned out to be:

Hi Dr. Schultz!

I thought I would drop you a note to let you know about my experience since the REU this summer. I of course, added the projects I worked on this summer to my resume. At our career fair this past fall I got responses that I never would have dreamed of. Several companies, when they saw the UAV listed offered me interviews immediately. A couple of companies mentioned that they are beginning UAV research and asked if I would be interested in helping out with that. I thought you may be able to use this information to get more students for next summer. I couldn't believe how excited the recruiters were to hear about my work!

Thanks again for the opportunity I had last summer. I appreciate it even more looking back.

6. Summary & Future Directions

The ten-week REU Site summer session uses a systems engineering approach to accomplish the scientific mission of designing a sensor system. Due to the short period of time available for each summer research experience, an aggressive schedule must be followed. This schedule allows for the full design, build, and field test phases of a sensor development effort to be completed within a ten-week timeframe. Data collection is also essential for an effective summer experience. As discovered in previous sensor development projects at UND, if data is not collected and analyzed, the students seem to lack a sense of accomplishment. This “closure” is a critical stage to achieve for both the REU Site participants and the management team to feel that the project was successful and worthwhile. For this to occur, the scope of the summer projects has to be appropriate and well-defined. While challenging, milestones are established for the group project that are achievable, with independent research projects identified for those team members who are overachievers. It is also important to scale the systems engineering projects appropriately so that each summer’s team has a fresh project to complete. Students are much more interested in the development of a new system than they are in continuing where another team has left off. This is the critical reason that there has to be a primary theme to all the activities throughout the course of the REU Site. It falls upon the management team to construct a cohesive theme with several individual research projects that can complement each other to create a truly outstanding undergraduate research program. Without this vision, the program loses focus and does not mature to the level that is desired.

As far as the direct benefits to the REU Site participants are concerned, the students receive training as systems engineers, which is vitally important to the modern technical workforce. This particular REU Site provided equal portions of technical workforce development and research experience to its participants. The participants also had a chance to practice their communication and teamwork skills, so they are better prepared for their future careers. A disadvantage to hosting an REU Site that builds a large-scale environmental sensor through teamwork is that each student generally does not have the time to focus on an individual problem in science or engineering, which is more representative of most graduate school programs.

Although documenting their designs is probably the least favorite activity among engineering students, they quickly learn the importance of document and revision control when they work on a large team. Furthermore, potential employers are quite excited about the students gaining this type of experience during their education. The most important lessons that the students take away from the sensor development projects are:

- Documentation is critical, especially for long-term (i.e., multiple academic year) projects.
- Designing subsystems is relatively easy, but designing their interfaces is more difficult because of coordination and teamwork issues. The need for accurate interface control documents and constant communication among team members is critical.
- Integration and test always takes twice as long as you expect in any large-scale project, so you must plan your timeline accordingly.

Learning about the regulatory process, which has included the Federal Aviation Administration for airborne payloads and the National Aeronautics and Space Administration for payloads developed for launch and/or operations in NASA vehicles[12], is extensive and time-consuming. It is also one of the most sought-after experiences by potential employers.

A number of the students learned that they do enjoy high-risk, high-reward research and development activities, while several decided that they would rather work on less risky design and test projects in the future. Most of the undergraduates involved in this program were not considering graduate school after they received their baccalaureate degrees, although they claimed that they wanted to attend graduate school during their telephone interviews. This was a great disappointment to the management team, as the original objective of hosting an REU Site was to train additional undergraduates in systems engineering principles so that they could contribute to future large-scale efforts as graduate students at the University of North Dakota.

As far as the direct benefits to the faculty mentors are concerned, the faculty learned how to better manage student teams and to work within the confines of highly variable undergraduate student learning curves. Faculty members are not typically trained in program or project management, but these are necessary skills for growing a research group. Furthermore, the faculty mentors are exposed to many practical sensor design issues, including harsh environmental conditions (e.g., rain, wind, heat, and cold) and hardware/software tradeoffs. Finally, this REU Site provided some important strategic directions for the future of environmental sensor and payload development at the University of North Dakota.

So, in the end, who learned more – the REU Site participants or the management team? It was beneficial to both groups for different reasons. The participants were exposed to the systems engineering process, which will be beneficial for their careers. The faculty mentors were able to dabble in new sensor development projects and to refine future projects. They also learned how to recruit and manage a relatively large team of students, and to understand what they are capable of accomplishing as a group undergoing the quintessential forming, storming, norming, and performing stages of team development.

What does the future hold? The design of ground-based environmental sensors is certainly the least glamorous when compared to the development of airborne and satellite payloads, but ground-based sensor networks can be built in a short amount of time with undergraduate research assistants. They are highly accessible and do not have significant mass or volume constraints. This technology will be extended to other types of remote sensing for wetland studies, possibly even broadening into interstellar science. However, wireless sensor networks still need extensive development before they will be truly beneficial. An area of continued research is the distribution of motes, as well as their functionality. Will off-the-shelf motes do what is actually needed to capture, store, and transmit environmental data, or will custom devices need to be developed for application-specific scientific missions? Furthermore, there will be a growing number of activities related to UAV environmental and civilian payload development over the next several years at the University of North Dakota. Using ground-based sensor networks to provide “ground truth” data from the field, and then correlating these sample points with airborne payload data that has much greater coverage will provide a wealth of research and development projects for years to come.

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