PolarCube: A Student Led CubeSat Mission

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The purpose of the PolarCube mission is to create a 3D temperature profile of the troposphere at the 118.7503 GHz diatomic oxygen resonant frequency. PolarCube will collect Earth surface and atmospheric temperature data using a passive microwave radiometer on a 3U CubeSat. The novelty of PolarCube is in proving the feasibility of passive microwave sensing on a CubeSat form factor; with technology designed, built, and tested entirely by students.

To accomplish this, PolarCube will be leveraging the architecture and heritage of a student designed and built 3U CubeSat bus, the Agile Low-cost Laboratory for Space Technology Acceleration and Research (ALL-STAR), from the University of Colorado at Boulder. The purpose of ALL-STAR is to provide the necessary support systems for a variety of space-based, research payloads with a rapid development cycle. PolarCube's research payload is a miniaturized radiometer, MiniRad, which will be one of the first and most advanced passive microwave sensors on a CubeSat. The objective is to collect microwave emissions at high spatial resolutions for remote sensing science and technological purposes.

The 118.7503 GHz diatomic oxygen resonant frequency has the ability to perform cloud penetrating temperature profiling. Through collaboration with the National Snow and Ice Data Center (NSIDC), the primary scientific goal is to study ice retreat in the polar regions. Militarily relevant objectives have been identified through PolarCube's participation in the University Nanosat Program (UNP), which includes mesoscale weather research, storm cell observations, hurricane warm core behavior, and terrestrial temperature detection with a 15-20 km spatial resolution. PolarCube has been awarded continued support from UNP by proving its design and program maturity at the 2015 Flight Competition Review.

The National (Naval) Ice Center (NIC), Air Force Research Laboratories (AFRL), and the Air Force Weather Agency (AFWA) have pledged their support and interest in PolarCube's novel technological potential. PolarCube has received three letters of support from each one of these respective military entities. With AFWA and NSIDC's support, a scientific data plan is being developed to identify how PolarCube's data could be applied to current weather models.

PolarCube is approaching flight hardware procurement and is projected to enter system characterization and testing by early Summer 2015. Additionally, it is planned that MiniRad will be fully calibrated and characterized at the National Institute of Standards and Technology (NIST), providing an unique opportunity for a student led CubeSat mission. A replica of MiniRad will be built and maintained at NIST for ongoing radiometer performance characterization. With PolarCube's current trajectory, it is anticipated that the mission will be ready for delivery in early 2016.

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Contents

Nomenclature

ACS	Attitude Control System
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AFWA	Air Force Weather Agency
AIAA	American Institute of Aeronautics and Astronautics
ALL-STAR	Agile Low Cost Laboratory for Space Technology and Research
AMSR-E	Advanced Microwave Sounding Radiometer-Earth
CalPoly	California Polytechnic State University
CDH	Command and Data Handling
CET	Center for Environmental Technology
COM	Communications
COSGC	Colorado Space Grant Consortium
CRS	Commercial Resupply Services
CU Boulder	University of Colorado at Boulder
DANDE	Drag Atmospheric Neutral Density Explorer
DMSP	Defense Meteorological Satellite Program
ELaNa	Educational Launch of Nanosatellites
EMR	Electromagnetic Radiation
EPS	Electrical Power System
FCC	Federal Communications Commission
GPS	Global Positioning System
IARU	International Amateur Radio Union
IceSat	Ice, Cloud, and Land Elevation Satellite
ISS	International Space Station
JPSS	Joint Polar Satellite System
MOCC	Mission Operations Control Center
MOPS	Mission Operations
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite Data and Information Services
NIC	National Ice Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
P-POD	Poly-Picosatellite Orbital Deployer
PEZ	Payload Extension Zone
UHF	Ultra-High Frequnecy
UNP	University Nanosat Program

I. Introduction

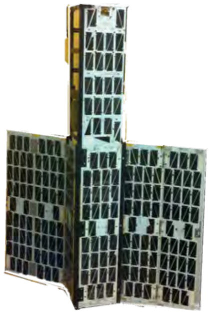

Figure 1: ALL-STAR 3U CubeSat

PolarCube is a 3U CubeSat that is designed to perform atmospheric temperature sounding of the Earth surface and troposphere using a radiometer centered at the 118.7503 GHz diatomic oxygen resonant frequency. Through this technology, PolarCube can provide an accessible, low-cost, fast development cycle, platform to augment weather monitoring assets that are currently used for global coverage. PolarCube was originally founded by three internal CU Boulder entities; COSGC, NSIDC, and CET in 2012. This effort was originally targeted toward the study of ice retreat in polar regions by virtue of NSIDC's direct interest. The scientific technology itself was originally designed at CET through the CU Boulder Electrical Engineering department, though that effort is now being combined with COSGC. The desire for increased accessibility, low cost and fast development cycle is facilitated by the use of the ALL-STAR program (Fig. 1) at COSGC.

This triad architecture provides the opportunity for students at CU Boulder to take full responsibility for the design, build, and testing of the PolarCube spacecraft. In early 2013 the PolarCube mission entered the UNP eighth cycle competition which enabled over 80 students since 2012 to get hands-on engineering experience. This past January, the PolarCube team was awarded second place in the competition which culminates in additional support from UNP-AFRL and a guaranteed launch opportunity. The PolarCube team is currently developing hardware to enter day-in-the-life testing this upcoming summer and environmental testing in early 2016. The goal is for PolarCube to be ready for launch by the end of 2016 to early 2017 and have a mission lifetime of approximately one year to verify the systems' capability for a potential future fleet.

II. Leveraging Student Experience

A. Leveraging Past Projects

The PolarCube team is comprised of an interdisciplinary, student led, group of students that have satellite build and delivery experience (Fig. 2). This has been enabled by COSGC and the opportunities that are provided through the consortia to students at CU Boulder. Since 1989, over 6,000 students have been directly involved in COSGC's hands-on space hardware programs. Three sounding rockets (CSOAR, CSHARP, HOMER) have been launched, along with three Space Shuttle payloads (ESCAPE, ESCAPE-II, and DATA-CHASER), four orbiting satellites (3CornerSat, Hermes, ALL-STAR, and DANDE), 10 sounding rocket payloads, 5 long-duration high altitude balloon payloads, and over 400 short-duration high altitude balloon payloads. In addition, students work on autonomous robotics projects and engage in telescope observing research and other faculty-led, space-focused research projects.

Figure 2: 2015 PolarCube Team at the Flight Competition Review

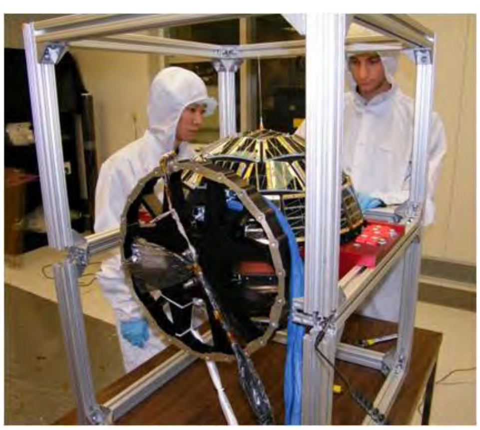

Figure 3: DANDE Integration Testing

The current PolarCube team has been able to directly leverage lessons learned from the DANDE and ALL-STAR/THEIA mission (along with other shorter development life cycle projects) as there are students from both of those missions on the PolarCube team. The DANDE mission was the second COSGC project that participated in the UNP (Fig. 3). In 2009 the DANDE mission was awarded first place in the UNP fifth cycle competition. The satellite was launched on September 29, 2013 aboard a SpaceX Falcon 9 v1.1 rocket. DANDE enabled over 100 students to gain hands-on experience and provided COSGC a baseline for mission planning and successful architecture build up. These lessons learned and experience have been leveraged on the PolarCube mission and have aided in PolarCube's success in UNP competition.

PolarCube has also heavily leveraged the student experience from the ALL-STAR/THEIA mission which began in 2009 and ended with a successful launch in 2014 (Refer to Section II.B. for more details). The core systems engineering team from the ALL-STAR/THEIA was carried into PolarCube's second year of development which was the ideal time to introduce technical and practical knowledge from these experienced students.

The ALL-STAR/THEIA mission provided students experience with: system integration and testing, protoflight Vibe (3 dB) testing, TVAC/Bakeout testing, CalPoly P-POD integration, which satisfied the ELaNa ICD, launch readiness review, frequency and operational licensing (NOAA, FCC, IARU), and operation of a mature ground system architecture (Fig. 4). All of these experiences have been directly applied to the PolarCube mission along with advising and mentoring from alumni from the ALL-STAR/THEIA, DANDE, and the Hermes mission. The team is assuring to do extensive training as older team members graduate and new students join the team to assure all practical and technical knowledge obtained by both the DANDE and ALL-STAR/THEIA teams are maintained through PolarCube.

Figure 4: ALL-STAR/THEIA Integration Testing

B. ALL-STAR Program Heritage

Figure 5: ALL-STAR Review

The ALL-STAR program was created through a partnership with the Lockheed Martin Company and the Colorado Space Grant Consortium with the goal to build a 3U CubeSat bus system that could support a variety of space-based missions for a one-year operational lifetime. The intent was to provide students the opportunity for real-life, hands-on experience during their undergraduate and graduate studies at CU Boulder (Fig. 5). The ALL-STAR program began in 2009, and since then has fully supported the THEIA mission.

The ALL-STAR bus contains power management, command and data handling, communications, and attitude determination and control systems all within a 1.5U form factor. The system features a deployable PEZ and two wings to increase the surface area of the space craft for solar cells (Fig. 1). All of the hardware (except the GPS module) on ALL-STAR is completely designed, built, and tested by students at COSGC (Fig. 6).

ALL-STAR's first mission was with the 1.5U THEIA payload, which was an Earth-imaging optical telescope. The ALL-STAR/THEIA mission successfully launched as a secondary payload on April 18, 2014 aboard SpaceX's Falcon 9 CRS-3 ISS resupply mission. The COSGC mission operations team (also fully comprised of students) at CU Boulder detected a 2.4 GHz S-Band signal carrier that matched the center frequency and amplitude from ALL-STAR/THEIA. It is believed that this signal carrier verified the deployment of the PEZ and wings along with the power-on of the spacecraft.

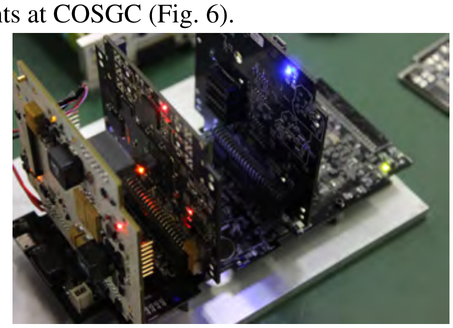

Figure 6: Integrated ALL-STAR Avionics: (L to R) EPS, COM, ACS connected to CDH Backplane

Upon completion of the ALL-STAR/THEIA mission, a root cause analysis for failure was conducted by the student team and documented to ensure future missions do not experience the same failures. The ALL-STAR bus was then revised to incorporate the lessons learned from ALL-STAR/THEIA. These revisions are encompassed in the ALL-STAR bus that PolarCube will be integrating with.

III. Radiometric Technology

The current meteorological satellite platforms, including DMSP, JPSS, AMSR-E, and IceSat, utilize a variety of microwave radiometric devices. The current systems are critical for military and commercial weather forecasting and some have been in use since the 1970's. While the current platforms often operate in a constellation format, with a series of individual satellites, they are vulnerable to gaps in coverage if a member of the constellation ceases to operate. These systems are high cost, and require a complex development cycle. PolarCube hopes to augment the current systems by providing a low-cost, rapid development cycle platform that can perform radiometric temperature sounding of the lower atmosphere with spatial resolution to the current platforms.

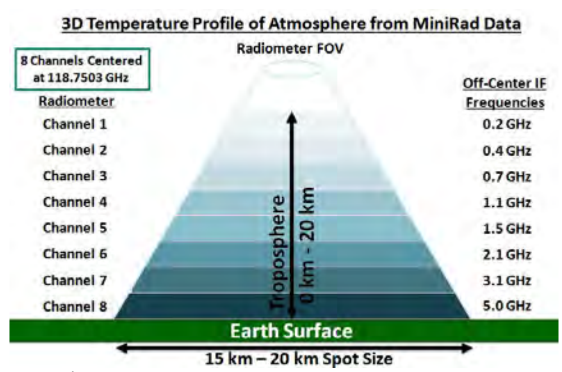

Figure 7: Tropospheric Temperature Sounding

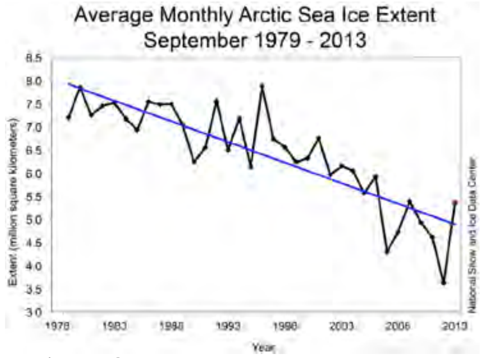

Figure 8: Decreasing Sea Ice Extent Trend

Atmospheric sounding provides characterization of altitudes that correspond to absorption lines, which are a function of temperature at a given altitude (Fig. 7). PolarCube will be one of the first 3U CubeSat to be capable of remote sensing from a low Earth orbit platform. Instrumentation using the 118.7503 GHz diatomic oxygen resonant frequency will provide brightness temperature measurements of thermal atmosphere emissions within the troposphere (0-30 km). These measurements will extend understanding of the processes that govern estimated global water and energy fluxes. The primary scientific objectives are focused on the study of polar regions, specifically the retreat of sea ice content (Fig. 8). The temperature heat flux concealed between cloud cover and ice surface is not currently characterized, and recently the predictions for sea ice retreat are not accurately modeling how this heat flux varies over seasonal cycles. Novel data sources and increased coverage of these regions would aid the understanding of the dynamics of the atmosphere and sea boundary for Navy, Air Force, NOAA, and NASA models. Greater atmospheric and sea/ice knowledge can aid those organizations dependent on weather and sea knowledge for an operational advantage or scientific study. This mission will advance key technology and provide critical data as identified by the Navy and Air Force strategic technology advancement plans.

A. Miniaturized Radiometer: MiniRad

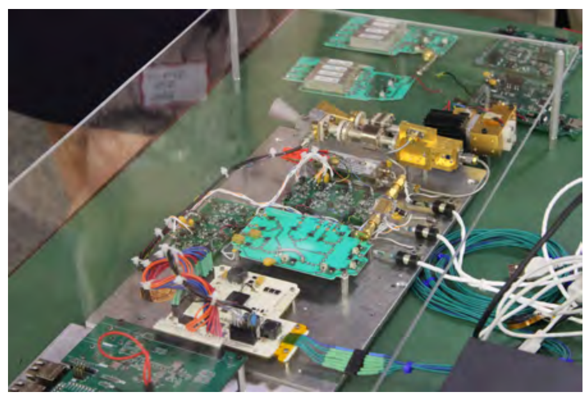
Figure 9: MiniRad Engineering Design Unit

MiniRad is the miniaturized, passive, microwave radiometer centered at 118.7503 GHz diatomic oxygen resonant frequency that encompasses 1.5U (approximately 10cm x 10cm x 15cm) of the PolarCube system. It is based on the technology that flew on the NASA ER-2 mission in 1986 which featured a 200 lb radiometer centered at 118.7503 GHz. MiniRad is comprised of four primary sections: radio frequency (RF), intermediate frequency (IF), digital carrier, and structures (Fig. 10). The RF section captures the desired EMR (specifically microwave) with a feedhorn antenna. The 118.7503 GHz frequency is then isolated and passed to the IF section. The frequency is then separated into eight channels centered around 118.7503 GHz corresponding to the 8 'slices' of the lower atmosphere (Fig. 7). The eight channels are then sent to the digital carrier which is responsible for communication between the MiniRad payload and the ALL-STAR avionics. Additionally, the digital carrier controls the pin diode on the RF section that is used for radiometric calibration, and manages power regulation for the MiniRad system.

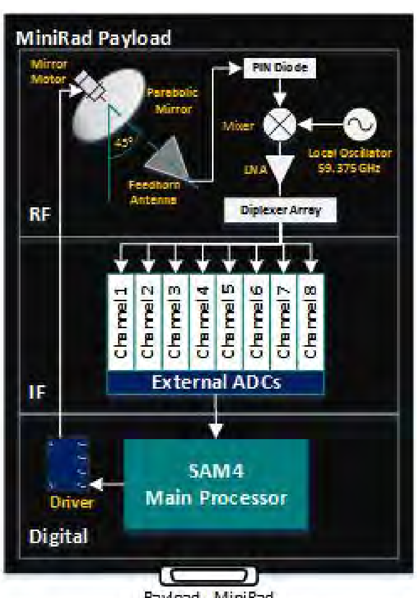

Figure 10: MiniRad Functional Block Diagram

The current feedhorn antenna design is being manufactured through a 3D aluminum printing process. This process decreases the cost of producing a feedhorn over conventional manufacturing while allowing for a rapid turn around. MiniRad's feedhorn is one of the first microwave antennas to be 3D manufactured. As this process is still relatively new, there are many obstacles that must be overcome. Two of the major obstacles the PolarCube team is dealing with for MiniRad's feedhorn design are accounting for chamfers and fillets in the design, and achieving a surface roughness of $\lambda/100$. These challenges are being addressed through PolarCube's collaboration with CET. Lavanya Periasamy, a PhD candidate working with Dr. Albin Gasiewski, has created performance simulations for MiniRad's feedhorn to determine the ideal design to account for the fillets and chamfers caused by 3D manufacturing. CET and PolarCube have also been working closely to determine polishing methods to achieve a required surface roughness of $\lambda/100$.

The desired performance for MiniRad is to have an accuracy of 0.5 K at the surface and 2 K at an altitude of 20 km, which is comparable to current meteorological platforms that PolarCube hopes to augment. The ground work for this goal was laid by a series of CU Boulder Electrical Engineering Senior Capstone Project teams. These teams created a working MiniRad prototype IF section along with a digital carrier. Their work was then passed on to the COSGC PolarCube team who continue to work with Dr. Gasiewski and CET to pursue the performance goals for MiniRad.

MiniRad is currently considered to be in a 'silver' stage with the majority of the desired functionality operational (Fig. 9). The IF section and digital carrier are both being revised based on architecture changes and flaws found in the previous revisions. The feedhorn is in the process of being 3D manufactured with the corrugated design that was simulated by Lavanya. With MiniRad's current trajectory, the goal is to work with NIST to provide characterization of the radiometer using their CROMMA facility. This will provide students on the PolarCube team a unique opportunity to work with NIST and experience the calibration and testing process standards NIST practices.

IV. Collaborators

A. University of Colorado Boulder

1. Colorado Space Grant Consortium

The Colorado Space Grant Consortium (COSGC) is a statewide program that provides Colorado students access to space through innovative courses, real-world hands-on satellite programs, and interactive outreach programs; COSGC is funded by NASA, as part of the National Space Grant Program. There are 52 consortia in the National Space Grant program, with one consortium in each state, in addition to Puerto Rico and Washington D.C.

CU Boulder is the lead institution for the COSGC, and houses multiple facilities to support student projects. These facilities include an ISO 7, Class 10,000, laminar flow clean room that is used for satellite integration and testing of flight hardware, along with assembly, integration, and electronics labs where hardware is designed, built, tested, and integrated. COSGC at CU Boulder also has a ground station complete with UHF and S-Band receivers and a MOCC, where the COSGC MOPS team communicates with student payloads on orbit. The CU Boulder consortium offers these resources to undergraduate and graduate students of different engineering disciplines providing them a unique opportunity to get hands-on experience early in their academic career.

2. National Snow and Ice Data Center

NSIDC specializes in remote sensing of snow, ice, climate, and other arctic features in the Earth's Polar Regions. Serving as a global database for cryosphere-related data, NSIDC ensures that past, present, and future science data remains accessible for studying the Earth and its climate.

The PolarCube mission maintains the goal of 118.7503 GHz diatomic atmospheric sounding and temperature profiling, preferably in the polar regions (assuming a launch to a high inclination orbit). Should a high inclination orbit be granted, PolarCube intends to map sea ice/open ocean boundaries and perform temperature profiling of the cryosphere. Regardless of the orbit provided to PolarCube opportunity PolarCube receives, NSIDC will process the metadata received by the MOPS team at COSGC receives from PolarCube. A thorough data plan is under development with NSIDC and AFWA to define mission success criteria.

3. Center for Environmental Technology

The Center for Environmental Technology (CET) was established within the University of Colorado at Boulder College of Engineering and Applied Sciences in 2006. CET is supported by NOAA to support advanced environmental technology development through funding and equipment donation. The director of CET, Dr. Gasiewski, is supporting the PolarCube mission through his former experience at NOAA as Chief of the Microwave Systems Development Branch of the Physical Science Division.

The goal of the CET is to develop advanced in-situ and remote sensors, sensor systems, and sensing techniques for the prediction and study of Earth's environment. This includes ocean, atmosphere, cryosphere and land. Through the PolarCube mission, the CET will contribute in the development of temperature sounding and rain cell mapping at spatial resolution on a 3U CubeSat developed by the COSGC. This will provide the potential of remote sensing through a cost efficient and compact design based on past technology developed by NOAA.

B. University Nanosat Program

UNP is a satellite design and fabrication competition for universities. It is jointly administered by the AFOSR, the AFRL, the AIAA, the Space Development and Test Wing and the AFRL Space Vehicles Directorate's Spacecraft Technology division. The primary objective for UNP is workforce development by providing lessons learned from building a complex system. The second objective is technology development at various design levels (architecture, system, and component). The final objective is to provide support for the development of space science research at US universities (Fig. 11).

UNP provides students the opportunity to not only start and end a full space mission but to also understand the definition of system and programmatic requirements (Fig. 12). Apart from system and program maturity, UNP emphasizes the projects' military relevance. PolarCube's involvement in UNP has allowed the student team to develop a wider narrative for mission applications apart from polar science studies originally developed with NSIDC, CET and COSGC.

Figure 11: DANDE Spin Test

Success of the PolarCube mission will demonstrate the feasibility of Department of Defense and Earth Science Missions objectives for a greater use of inexpensive satellite platforms that can potentially improve weather and sea/ice modeling. This philosophy can, in the future, expand to include complimentary measurements and fractionated systems across multiple platforms for global coverage and low latency missions in accordance with the U.S. Air Force Technology Horizons for fractionated/distributed small satellite systems.

Figure 12: PolarCube hardware demonstration at FCR

The U.S. NIC have communicated their interest in the PolarCube mission. Through their affiliation with NOAA NESDIS, the main point of contact, Dr. Clemente-Colon, has expressed his interest in applying the results of PolarCube to NIC. PolarCube has recently received a letter of support from AFRL (AFMC) Kirtland Air Force Base by John R. Roadcap expressing his interest in microwave radiometers and its potential for supporting operational weather forecasting. PolarCube data could be used in a collaborative effort to increase the fidelity of mapping campaigns for sea-ice extent helping to fulfill several action items presented in the 2009 U.S. Navy Arctic Roadmap. With further communication the technological potential PolarCube has in severe mesoscale weather modeling, NIC and U.S. Air Force could apply high resolution weather data to personnel management.

Additionally PolarCube has also received a letter of support from Air Force Weather Agency's (AFWA) Chief Environmental Characterization Flight, Dr. Jeff Cetola, indicating the potential to improve emissivity models through small scale radiometric missions. The PolarCube team at CU (comprised of COSGC, CET, and NSIDC) are working toward aligning mission success criteria with AFWA. The team is currently developing a data plan with NSIDC and AFWA to fully understand how the missions radiometric data can help augment current emissivity models.

V. Conclusion

To date, approximately 80 students have worked on the PolarCube project from the original concept and design of MiniRad, up through the UNP eigth cycle flight competition review. PolarCube is approaching flight hardware procurement and is projected to enter system characterization and testing by early Summer 2015. The current trajectory will provide students with experience of integrating the PolarCube system, and conducting characterization tests including day in the life, long range communications, charge cycle, and command execution. PolarCube is planned to undergo environmental testing and delivery in mid to late 2016. Once on orbit, students will begin mission operations to communicate with PolarCube and preliminary data processing.

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VI. Acknowledgments