PolarCube: An Advanced Radiometer

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1 Abstract

The PolarCube mission will collect Earth surface and atmospheric temperature data using a passive microwave radiometer operating at the 118.7503 GHz O_2 resonant frequency. To accomplish this, PolarCube is utilizing an existing 3U CubeSat bus, the Agile Low-cost Laboratory for Space Technology Acceleration and Research (ALL-STAR), designed and built entirely by students at COSGC.

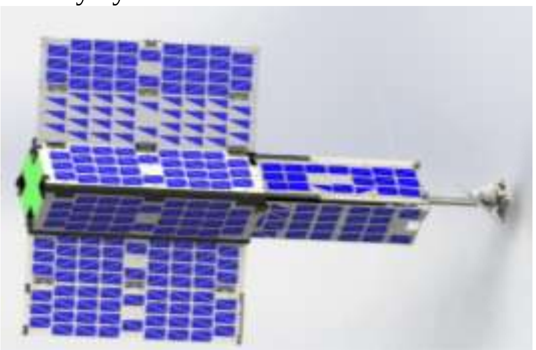

Figure 1: PolarCube Spacecraft in Deployed Configuration

The PolarCube radiometer (science instrument), "MiniRad" will be one of the first and most advanced passive microwave sensors centered at 118 GHz to be flown on a CubeSat. The objective is to collect brightness temperature spectra at high spatial resolution at a low cost for remote sensing science and technology evaluation purposes. Microwave emissions are focused into a radiometer feedhorn antenna using a deployable parabolic mirror spinning at a rate of 1 Hz. This allows the radiometer to create a temperature map "image" of the Earth's surface and atmosphere.

Applications of the data include:

- Atmospheric temperature profiling
- Sea ice/open ocean boundary detection and mapping
- Severe mesoscale weather observations
- Terrestrial heat detection
- Characterization of high-frequency communication bands through cloud cover.

The technology PolarCube will implement, allows for temperature sounding at spatial resolution up to two times better than AMSU A/B (a current meteorology satellite). Therefore, this significant improvement in spatial resolution has the potential to increase the performance of weather modeling.

PolarCube is currently affiliated with various organizations, the most prominent being Air Force Research Labs. PolarCube is a current competitor in the University Nanosat Program (UNP), which culminates in a launch opportunity for the winning team at the Flight Competition Review (FCR). Additionally, organizations including the National Snow and Ice Data Center (NSIDC) have pledged support in processing mission data.

PolarCube hardware is designed, built, and tested entirely by students. The team is highly interdisciplinary featuring a range of engineering disciplines comprising both undergraduates and graduates. The project is currently in the Critical Design Review (CDR) phase and is approaching system prototyping. A full engineering design unit is anticipated by August 2014 to be presented at the Small Satellite conference in Logan, Utah. The FCR is the major milestone for PolarCube, which is scheduled for January 2015.

2 Mission Overview

PolarCube Mission Statement:
To perform tropospheric temperature sounding for observation of sea ice/open ocean boundaries, for providing representative data inputs to tropospheric weather models applicable to severe mesoscale weather forecasting, and for cloud penetrating thermal profiling and imaging at a high spatial resolution.

2.1 Mission Objectives

(Goals 'G' and Constraints 'C')

- Study the relationship between low altitude atmospheric temperature structure and ground surface (sea ice cover) (G).
- Provide representative brightness temperature data inputs to tropospheric weather models applicable to weather forecasting (G).
- Provide cloud penetrating thermal profiling and imaging data (G).
- Achieve spatial resolution approximately twice that of operating temperature sounders and significantly closer to the natural horizontal spatial scale convention (G).
- Study arctic cloud cover changes using additional data from ATMS NPP-Suomi (G).
- Provide early demonstration of temperature sounding using established 118 GHz O_2 resonance (G).
- Perform science data collection over two seasonal transitions (G).
- Provide a low-cost satellite to serve as a pathfinder for fleet based global passive microwave sensing (G).
- Use of Colorado Space Grant Consortium existing ALL-STAR 3-axis 3U CubeSat bus design (C).
- Use Center for Environmental Technology (CET) 118 GHz Radiometer components (C).

2.2 Atmospheric Temperature Sounding

Atmospheric sounding provides characterization of altitudes that correspond to absorption lines (function of temperature given altitude as seen in figure 2). PolarCube will be one of the first 3U CubeSats to be capable of remote sensing from a low Earth orbit platform. Instrumentation using the 118.7503 GHz O_2 resonance will provide 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. PolarCube's collaboration with the COSGC ALL-STAR 3U CubeSat allows ~10-20 km spatial resolution of the Earth's surface for ~1yr (dependent on orbit altitude).

Satellites with similar radiometric capabilities contain the Advanced Microwave Sounding Unit (AMSU), which analyzes moisture and temperature through atmospheric sounding at microwave frequencies, making it ideal for meteorological applications. The technology PolarCube will implement, allows for temperature sounding at spatial resolution up to two times better than AMSU A/B (a current meteorology satellite). Therefore, this significant improvement in spatial resolution has the potential to increase the performance of weather modelling.

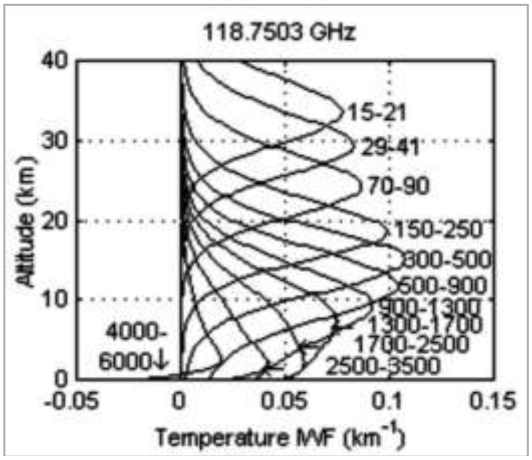

Figure 2: Altitude vs. Temperature: Profile for 118 GHz

2.2.1 Arctic Research

The retreat of summer sea ice in the Arctic Sea and the region west of the Antarctic Peninsula (Parkinson and Cavalieri 2012; Cavalieri and Parkinson, 2012) has profound effects on the lower troposphere, particularly during late summer and autumn. With increased areas of ice-free Open Ocean and summertime solar warming of the uppermost ocean surface, there is a large sensible heat and moisture flux between the ocean and atmosphere as winter approaches.

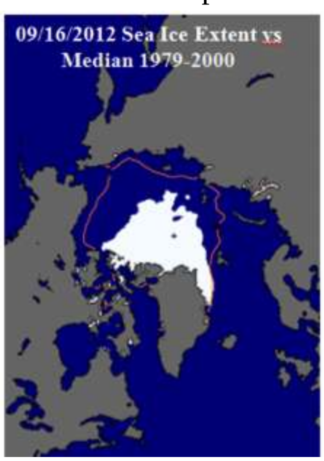

Figure 3 Sea Ice vs Median 1979-2000

This flux has local effects on the atmosphere that may increase storms in the Arctic (Screen et al., 2011). Additionally, the increased fetch due to the loss of ice, combined with increased storminess enhances coastal erosion (Overeem et al., 2011) and ocean mixing. The effect of sea ice loss (Fetterer et al., 2002) has been observed via increased cloud cover over ice-free regions in satellite data sets (Liu et al., 2012) as seen in figure 3. This transfer of heat and moisture is occurring in the Arctic at a scale and intensity large enough to impact polar-wide circulation patterns (e.g., Serreze et al., 2009; Serreze et al., 2011; Stroeve et al., 2012), and in turn may affect temperate and boreal climate (e.g., Francis and Vavrus, 2012; Overland et al., 2011; Overland and Wang, 2010). Adjacent areas with partial or complete sea ice coverage have far smaller levels of atmosphere ocean interaction, latent and sensible heat transfer. Accurate knowledge of the local tropospheric response to sea ice changes is crucial to understanding and properly modeling the response of the global atmosphere and potential radiative feedbacks to sea ice (e.g., Porter et al., 2011).

The response to sea ice and clouds of the highest IF frequency channel used in MiniRad will be similar to that provided by the 89-GHz channel on the NASA Aqua AMSR-E sensor, which provides current high-resolution data for sea ice concentration mapping. However, the additional channels closer to the 118 GHz line center will provide a temperature-profiling capability to be used for correlating sea ice state with tropospheric temperature variations, specifically within the lower troposphere. If this data is used in conjunction with the data from operational polar-orbiting sensors (NPP.ATMS, JPSS, Eumesay) it is possible to retrieve cloud liquid water density and measure high densities of cloud ice. Weather patterns during seasonal transition effects on Arctic cloud cover could be observed and can be correlated with data from NSIDC.

2.2.2 Meso-Scale Weather

Atmospheric temperature sounding through the technology PolarCube is implementing additionally offers the ability to study sea ice/open ocean boundaries and the analysis of severe meso-scale weather phenomena. For example, correlating PolarCube temperature profiling data with data from the NOAA Microwave Humidity Sounder (MHS) would allow the detection of severe open ocean storms such as tropical cyclones. Therefore, PolarCube has the potential to provide high resolution data for meso-scale weather systems such as the hurricane shown in Figure 4.

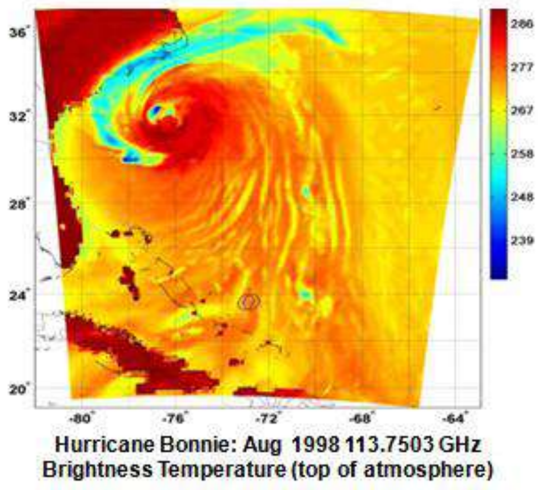

Figure 4 Hurricane Bonnie

Cyclonic storms are predominantly characterized by low pressure. This is triggered by an increase in humidity and a decrease in temperature. Because of this, PolarCube will be capable of providing temperature readings in open ocean areas through cloud ice analysis. These readings can provide single cell scale length storm surface area readings of up to 15 km. This analysis can be further achieved when used in collaboration with a humidity sounder, such as MHS, to detect a tropical cyclone/hurricane or other severe meso-scale storm.

Through the use of PolarCube, representative data inputs to tropospheric weather models applicable to sever meso-scale weather phenomena. For future applications PolarCube can provide high resolution (10-20km) real time warm core behavior data of hurricanes/mesoscale weather.

2.3 System Operational Modes

In order to collect tropospheric temperature profiling and sea ice/open ocean imaging data PolarCube will investigate one mode for minimum mission success (1) along-track scanning and will investigate a secondary mode (2) cross track scanning (sounding). In stabilized mode, PolarCube will take sub-track data samples of the earth in the direction of the velocity vector for instrument verification purposes. The data collected in the cross-track direction will be sampled at the Nyquist rate, which will provide rasters (strips of data) that will not need aliasing techniques post flight for matching consecutive samples. In the cross-track mode PolarCube will spin the radiometer instrument at certain speeds up to 1 Hz in order to provide a "temperature map" of the temperature profiling data. Figure 5 shows a brief description of these modes and a high level explanation of their data output. Each green circle in this image represents one data sample of 16.5 km resolution.

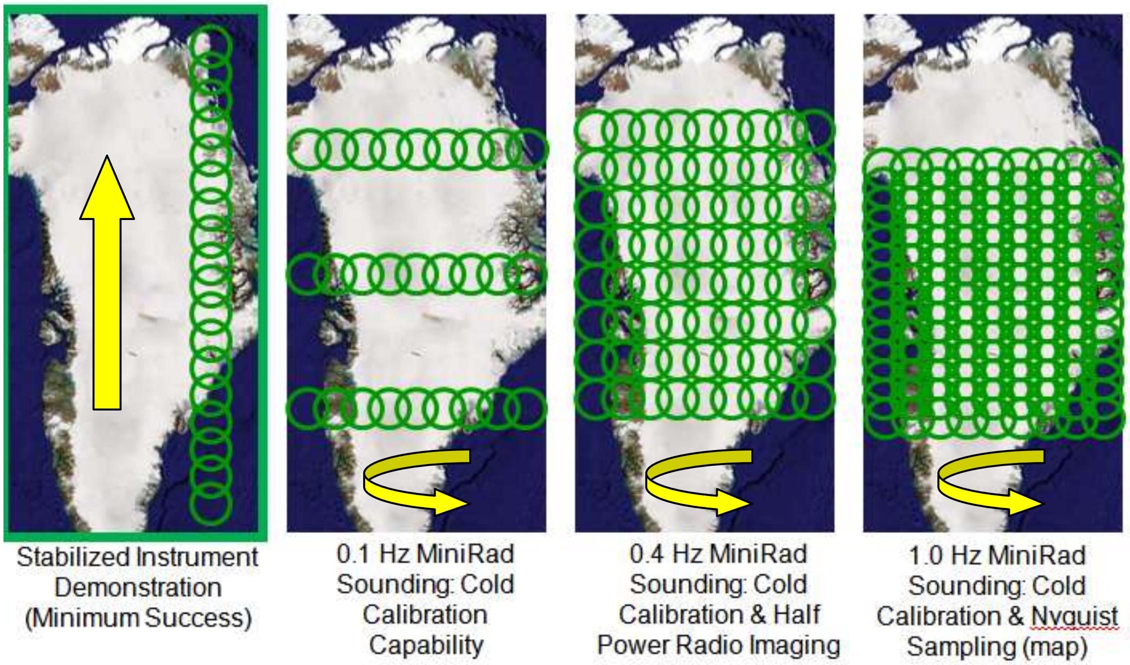

Figure 5 PolarCube Operational Modes Description over Greenland (Not to Scale)

2.4 ALL-STAR Bus System

The COSGC Agile Low-cost Laboratory for Space Technology Acceleration and Research (ALL-STAR) Bus provides an optimal foundation for the MiniRad sensor and the PolarCube mission. The bus is designed to accelerate the rate at which small research and technology based payloads are able to be launched by providing the satellite bus.

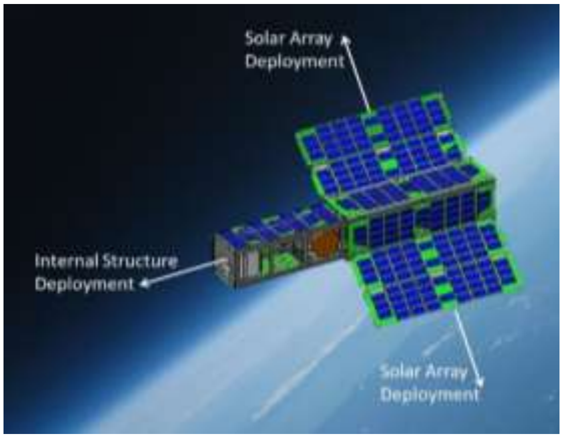

Figure 6: ALL-STAR Bus in Deployed Configuration

The model of this system is shown in Figure 7. By using the ALL-STAR bus, the PolarCube team will leverage the core satellite systems bus and therefore incur lower risk by using a largely designed student built bus.

The first launch of an ALL-STAR bus will be in support of the THEIA (Telescopic High definition Earth Imaging Apparatus) mission that will take place in the spring of 2013. Much of the ALL-STAR system is CAD designed, built and system characterization has taken place. Various system tests, including vibration testing for key risk areas have occurred.

In order to successfully integrate to the ALL-STAR bus, PolarCube must comply with the ALL-STAR payload requirements and specifications as described in the ALL-STAR payload interface control document (ICD). Through compliance with the ALL-STAR bus, PolarCube will serve as a compact and low-cost form of remote sensing in comparison with similar technologies such as ATMS, AMSR, and

MLS. The minimum mission success of PolarCube is projected to be fulfilled with the current ALL-STAR designed this can be seen in Table 1 where ALL-STAR Specifications are compared to PolarCube compatibility and system needs for the science instrument MiniRad.

2.5 MiniRad System

The PolarCube technology consists of a radiometer (passive microwave spectrometer with eight channels centered around 118.7503 GHz oxygen emission line) also known as the Miniaturized Microwave Radiometer (MiniRad). MiniRad is a space-qualified payload that is currently being designed and prototyped as a senior capstone design project by a team of CU engineering students at COSGC. The functional diagram can be seen in figure 9. This team is closely mentored by Professor Gasiewski, which has direct experience with the study of the passive microwave spectrometer through aircraft experiments dating back three decades.

2.6 Data Analysis

This information will be further assessed by interpolating the data using the weighting functions in Figure 10. Each data sample will contain information from all eight channels centered at the 118.7503 GHz resonance and will provide temperature data (correlated to voltages) that are a function of altitude. The eight channels provide high vertical resolution capability within a small satellite volume.

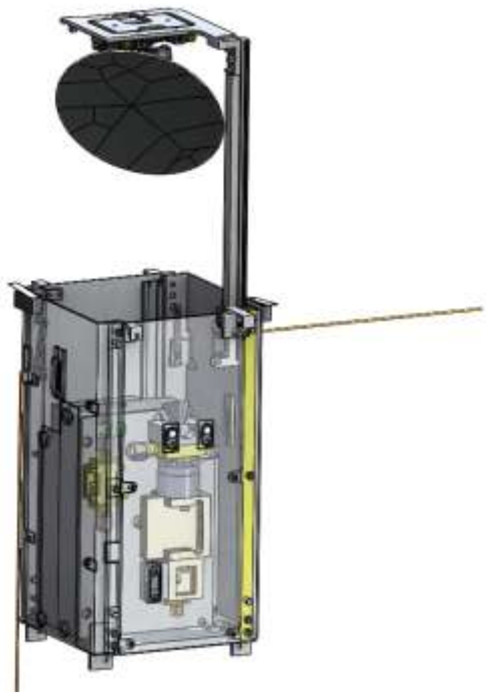

Figure 7: MiniRad sensor integrated in the PolarCube structure in the deployed position

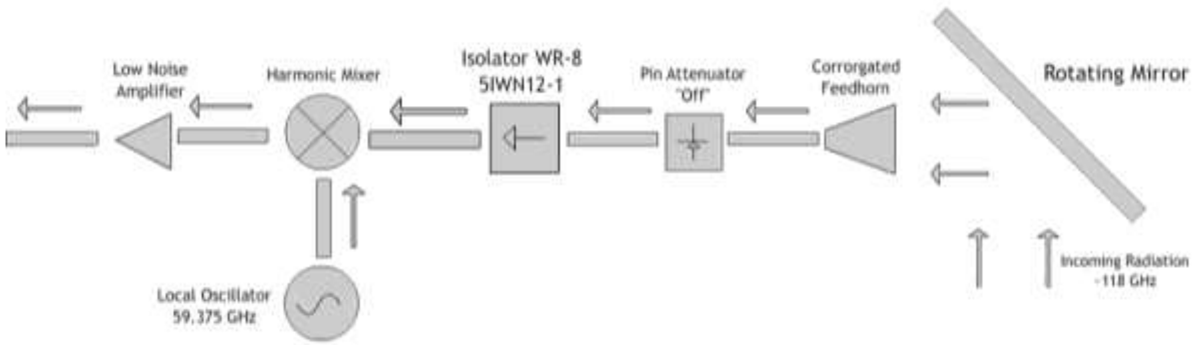

Figure 8: MiniRad System

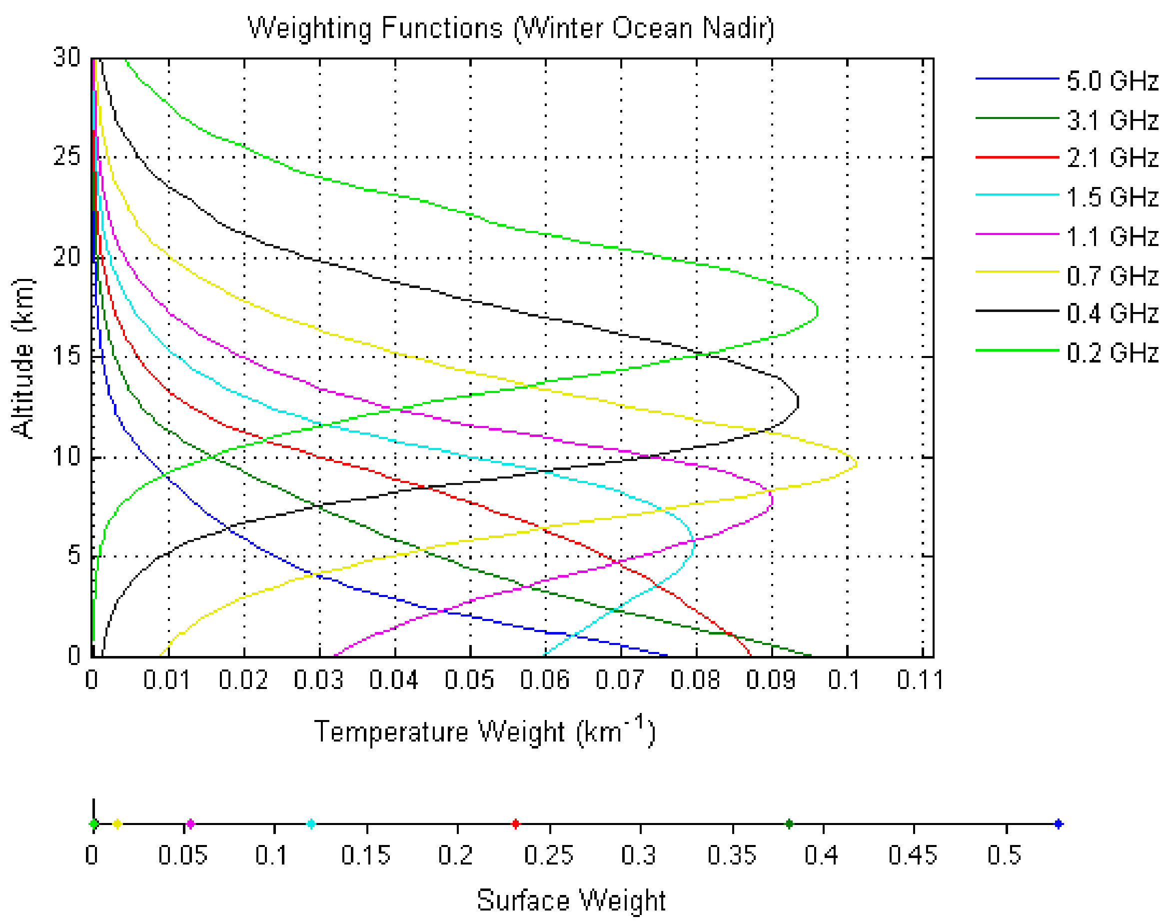

Figure 9: Weighting Functions (Winter Ocean Nadir)

2.7 Future Development

The PolarCube project has the potential to be a precursor to the development of a fleet observation concept providing both high spatial and temporal resolution global observations of the atmosphere for weather forecasting purposes. This will be verified after the first technology demonstration of the MiniRad instrument. The Precipitation and All-weather Temperature and Humidity (PATH) Array Constellation Satellite (PACSat) concept can be a low cost means of providing passive microwave weather data using up to 30-50 small satellites in staggered orbits. PolarCube will demonstrate the feasibility of CubeSat passive microwave satellite payloads and through their low cost and high resolution, provide a pathfinder for establishing a constellation of such satellites. Current passive microwave weather sensors are both expensive and singularly risky, while a fleet of low-cost sensors could provide a robust means of obtaining the data needed for radiance assimilation for both short and long term weather forecasting.

3 Success Criteria

For the PolarCube mission a designation between engineering and mission success has been identified as the mission objectives also include the use of the ALL-STAR 3U CubeSat bus and its successes. Bus commissioning and to a certain extent payload commissioning have been grouped as engineering success, whereas payload validation and scientific data product production are related to minimum and full mission success. Since there is a lead up to full mission success as a criterion is first observed to be successful its success is required to subsequent levels in the mission.

Minimum mission success for PolarCube is defined by:

- 1/6th (60º) orbital science duty cycle
- 10 orbits of science data total (nonconsecutive)
- Any location of Earth

This will prove that the MiniRad system is not only functional but it will also demonstrate the potential of improving the spacecraft configuration to a spinning/sounding mode for future mission plans. The following table describes specific criteria that PolarCube mission may meet depending on the success of each criteria itself. It is shown that the criteria that must meet Engineering Mission Success (physical objective met directly by spacecraft) is directly associated with fulfilling Minimum Mission Success in orbit.

4 Military Relevance

The atmospheric profile and sea ice interactions of the Polar Regions are in a constant state of flux, and recently the predictions for sea ice retreat are not accurately modeling these 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 depending 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.

The U.S. National/Naval Ice Center (NIC) have communicated their interest in the PolarCube mission. Through their affiliation with NOAA National Environmental Satellite, Data, and Information Services (NESDIS), our point of contact Dr. Clemente-Colon has expressed his interest in applying the results of PolarCube to NIC. We are currently in the process of contacting the U.S. Air Force further to communicate the potential PolarCube has in the weather prediction and technology aspect. 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 meso-scale weather modeling, NIC and U.S. Air force could apply high resolution weather data to personnel management.

5 PolarCube Team and Collaborators

5.1 PolarCube Team

The PolarCube team at the University of Colorado at Boulder is comprised of experienced senior personnel experienced in spacecraft bus and radiometer design and testing, atmospheric science, snow and ice data analysis, and student teams developing both the ALL-STAR spacecraft bus and radiometer payload. The current PolarCube team has satellite build and delivery history for the following satellites:

- Hermes 1U CubeSat delivered and launched 2011
- DANDE Micro-satellite delivered and launched, in operation from September 2013 to present
- ALL-STAR-THEIA 3-Axis stabilized 3U CubeSat bus delivered and set for launch March 2014

As well as experience in near space sub-orbital projects (i.e. high altitude balloon platform & sounding rocket program). The team works closely with academic experts and partakes in active mentoring with current student, alumni, and faculty.

The satellite bus and integrated microwave imaging radiometer payload are anticipated to provide up to 16.5 km spatial resolution images of ~1000 x 1000 km regions during a nominal one-year on-orbit mission to be launched under the NASA- Educational Launch of Nanosatellites (ELaNa).

The raw data will be analyzed by COSGC (Colorado Space Grant Consortium) and NSIDC (National Snow and Ice Data Center) to determine the atmospheric vertical temperature structure coincident with sea ice fraction and study the spectral signatures of atmospheric convective precipitation.

5.2 Mission Collaborators

5.2.1 CET Radiometer Technologies

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 the National Oceanic and Atmospheric Organization (NOAA) to support advanced environmental technology development through funding and equipment donation. The director of CET, Professor Al 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.

CET currently owns and maintains a wide range of radiometric and radar sensing and test equipment, including the following:

- The Polarimetric Scanning Radiometer (PSR) system consisting of three operational scanheads, three operational aircraft positioners, the GSR ground-based positioner, data acquisition and motion control hardware.
- Radiometers modules at many microwave frequencies between 1.4 and 500 GHz.
- Precision radiometric polarimetric and non-polarimetric calibration
- Support hardware, test equipment, components, and antennas.
- Microwave test equipment for full network analysis capability up to 140 GHz.
- A 20-TB data server and extensive internet network to support up to ~50 students and professional research staff members.
- Version-controlled software for radiative transfer and propagation

research, and radiometric and radar data analysis, processing, and display.
- An electrostatically shielded quite room for radiometer testing.
- Ready access to a number of Boulder-based CAD-ready machine shops, antenna test chambers, optical sensor laboratories, and environmental test chambers is available to CET members.

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.

5.2.2 Capstone

The current progress of the MiniRad sensor done by the senior capstone design project team is completion of test report including resolution between actual versus expected results. The capstone design project team must follow strict deadlines within their respective program, through mentorship and guidance provided by faculty the capstone team will have acceptance test demonstration for Instructors, staff, and sponsors by the end of April 2013. Further demonstrations of the MiniRad sensor will be completed between April to May of 2013 which will provide the PolarCube team a fully prototyped MiniRad sensor with proper system integration capabilities to test for a form factor design by the end of May 2013.

5.2.3 NSIDC

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. All polar data would then be provided to NSIDC for distribution and analysis.

5.2.4 COSGC

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.

The COSGC branch located at the University of Colorado at Boulder facilitates numerous student projects, including the ALL-STAR 3U CubeSat Bus and the PolarCube Mission. PolarCube is a 3U CubeSat based on the existing ALL-STAR bus design. The PolarCube project will integrate a radiometer payload with the ALL-STAR bus and provide associated pre-launch testing and algorithm development. The use of COSGC’s ALL-STAR bus for this mission will prove the adaptability of its 3U bus for a sensor not specifically considered during the design phase.

The PolarCube Mission also provides the opportunity for potential COSGC collaboration with several entities, including but not limited to: the United States Air Force, United States Navy, United States Department of Defense, CET, NOAA, and NSIDC. Inter-collegiate collaboration is also encouraged through the cooperation of COSGC personnel with the Electrical and Computer Engineering Department Senior Design Curriculum and the Director of NOAA-CU Center for Environmental Technology, Dr. Albin J. Gasiewski.

6 References

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